Costs and primary energy use of energy supply options to buildings of different energy efficiency levels

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ABSTRACT

An appropriate energy solution for buildings depends on the scale of demand and the availability of the surrounding technical infrastructure. Building energy demand can be altered by the application of various energy efficiency measures whereas the performance of the energy supply system can be changed by the involvement of various technologies. As a result, optimal energy supply options could depend on various parameters that depend on specific contexts. In this study, different options to supply energy to apartment buildings of different energy efficiency levels in Sweden are investigated. Different renewable-based alternatives to produce heat and electricity based on various state-of-the-art technologies are considered. The optimizations are based on the hourly variation throughout the year of energy demand and of different energy supply systems that change with the ambient conditions such as temperature and solar radiation. The results prove that optimal options for a building depend on its scale of energy demand and on the availability of technologies in the market. Also, there is a tradeoff between monetary costs and primary energy use in supplying energy to apartment buildings. This study shows that it is essential to consider the interaction between energy demand and supply to estimate the costs and primary energy use for energy supply alternatives. A heating system with an electric heat pump shows to be primary energy efficient option whereas that with a wood pellet boiler is a more cost efficient once. However, an energy supply option based on a combined heat and power unit using fuel cell technology could potentially be the most cost- and primary energy efficient option for buildings with low energy demand.

Keywords: building energy demand, combined heat and power, energy efficiency, primary energy use, cost-optimal option

Nomenclature

BST: biomass-based steam turbine
CHP: combined heat and power
EHP: electric heat pump
O&M: operation and maintenance
PV: photovoltaic
SNG: synthetic natural gas
SWH: solar water heating
T&D: transmission and distribution
WPB: wood pellet boiler
WST: water storage tank
µCHP-FC: micro-scale CHP using fuel cells
µCHP-GE: micro-scale CHP using gas engine
µCHP-SE: micro-scale CHP using Stirling engine

1. Introduction

In the global energy system in 2010, energy for buildings accounted for approximately 33.5% of the total final energy demand and is mainly in the forms of heat and electricity (IEA 2012). In the EU-28, the building sector is the largest energy end-user and accounted for approximately 40% of total final energy use and for 55% of the total electricity use, both in 2012 (Gynther et al. 2015). Therefore, efforts for a more environmental-friendly energy system with high levels of energy security should consider energy use in the building sector as an important area to be investigated.

Electricity for the building sector is currently provided by a regional power grid, connecting suppliers and users across long distances. Connection of power producers and end users can be done efficiently via a transmission and distribution (T&D) network. As a result, production of electricity can be far away or close to end users. With different incentive mechanisms for onsite power production such as net energy metering systems, buyback programs and feed-in tariff structures, small-scale electricity producers are becoming more common. This creates opportunities for involvement of energy- and cost-efficient energy supply options.

In regions with cold climates, primary energy use for space and hot water heating is significant. In the EU, heat for the buildings sector comprises about 56% of the total heat used (Sanner et al. 2011). Unlike in other sectors, heat for space and hot water heating in the building sector are at low temperature (Werner 2007; Larsson 2009) which could be recovered and produced from various industrial processes as waste heat and local resources as ambient and solar heat. However, heat losses during transportation over long distances inhibit the forwarding of heat from sources to end users. Also, seasonal variation of heat demand and the mismatch between available heat source and consumption throughout the year could make its production costly. As a result, district heating systems are normally possible in areas of high population density even though this type of heating is considered as an energy efficient option for buildings (Truong et al. 2015).

Of the heat production options, the heat production using combined heat and power (CHP) units could be a cost- and primary energy efficient option at large scale of district heat demand. However, the favorable conditions from large-scale district heat production systems are site specific. Also, heat distribution losses are inevitable and can be significant, especially for district heating systems with low heat density (Nussbaumer and Thalmann 2014). At a small scale of heat demand and in comparison to small-scale district heat production systems, the local heat production options of electric heat pump (EHP) and wood pellet boiler (WPB) emerge as a primary energy- and a cost-efficient option, respectively (Truong et al. 2015).

CHP production at the demand side could be an attractive option when suitable fuel sources are accessible. The local production of heat and electricity could reduce T&D losses for both electricity and heat. Therefore, this option could improve the overall conversion efficiency and also the energy system reliability. Today, different micro-scale CHP units are available for use in buildings. A CHP unit using a gas engine is a proven technology with more than one hundred thousand units installed (Danish Energy Agency 2013), and could be suitable for local heat and electricity production. Also, CHP units using a Stirling engine are currently approaching commercial market (Orr et al. 2011; Danish Energy Agency 2013). Furthermore, the development of fuel cell technology with reliable operation, high power-to-heat ratio and good performance at part-load operation (Danish Energy Agency 2014) could promote further expansion of micro-scale CHP units for end-users.

In such CHP technologies, fossil gas is the common fuel source. In the EU context, fossil gas is increasingly used, especially for a long term scenario and when lower carbon energy systems are targeted (IEA 2013). Fossil gas is predominantly used for power generation in centralized power plants with limited overall conversion efficiency compared to CHP production. Applications of gas-based energy conversion units are further strengthened within the context of renewable-based energy systems by the promising option of bio-synthetic natural gas (SNG) production from forest biomass (Heyne 2013). As a result, the use of biogas for micro-scale CHP units could be an energy efficient option.

An optimal energy supply option for an application depends on the availability of fuel sources, technologies, and the scales of energy demand. For the building sector, where heat and electricity demands vary throughout the year, scale of demand is also influenced by the size of the building and its energy efficiency levels. As a result, an optimal energy supply option is site dependent.

This study analyzes different options to supply energy to an apartment building with two different energy efficiency levels in Sweden. Different renewable-based alternatives to produce heat and electricity based on various state-of-the-art technologies are considered. The electricity production options include large centralized power production units and solar photovoltaic (PV) systems of different scales. The heat production options consider different local heat production alternatives including micro-scale CHP units. The optimizations are based on hourly variations throughout the year of energy demand and of different energy supply systems due to the varied ambient conditions.

2. Method and Assumptions

Different options to supply heat and, if possible, electricity for two building versions having different levels of energy demand are considered. Electricity production and use can be balanced by the grid network and therefore is considered under a regional condition. However, heat production depends on the demand which varies with time and seasons. In each case, total cost of energy supply and primary energy use for energy purposes are estimated. Primary energy use of the building is calculated under the overall energy system perspective. Under this perspective, increases or decreases of energy use at each instance of time are balanced immediately by the energy conversion units operating as marginal production units. This study limits on different options for the energy supply system from primary resources to the final heat and electricity distributed stations within the building.

2.1. Case-study Building

An existing apartment building constructed in 1995 in Växjö, Sweden is used as a case-study building. This apartment building has 4 stories and 16 apartments with a total heated floor area of 1190 m^2. The annual total heat and electricity use of this building is approximately 114 MWh and 54 MWh, respectively. However, there are different energy efficiency measures which could strongly alter the heat and electricity consumption for this building, including improved water taps, improved thermal properties for the exterior walls and roof, replaced windows and doors by triple-glazed units, incorporated ventilation heat recovery unit and efficient (Gustavsson et al. 2011; Truong et al. 2014). As a result, an energy efficient version of this apartment building could achieve 48.5 MWh and 35 MWh of heat and electricity use, respectively.

Figure 1 shows the profiles of heat and electricity use for the existing version and energy efficient version of the case-study building. The profiles of heat use were based on VIP+ simulation program (Structural Design Software 2008) as shown in Truong et al. (2015) whereas the profiles of electricity use were based on estimations considering its seasonal variations in Sweden (Sveriges Centrum för Nollenergihus 2012).

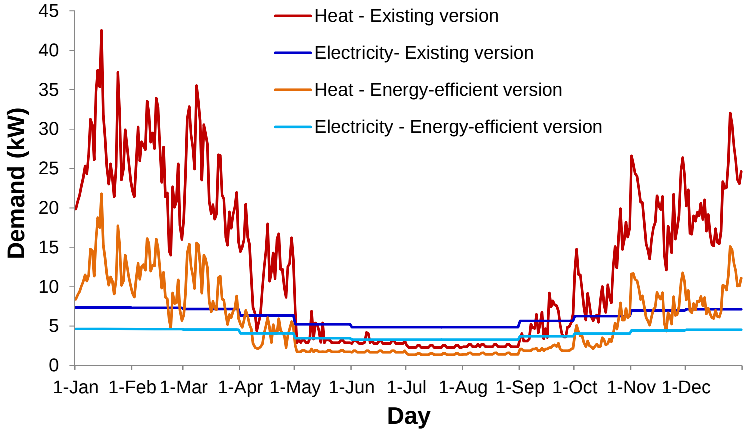


Figure 1. Profiles of heat and electricity use during 2013 for the two building versions

Profiles of heat and electricity use for these two building versions are used to elaborate the differences of energy demand on the costs and primary energy use for the energy supply system. Therefore, investment costs for the building to achieve different levels of energy efficiency are not considered.

2.2. Energy Supply Options

Different pathways using renewable energy resources are evaluated. For electricity, three technologies for standalone production are considered, including: i) biomass-based steam turbine (BST); ii) off-shore wind power; and iii): solar PV panels. Solar PV panels can be installed locally or centrally and connected to the regional grid. A roof-top solar PV system at a building is assumed to reduce T&D losses of the produced electricity.

Besides, different alternatives to supply heat are considered, including: i) ground-source EHP using electricity from standalone power plant; ii) WPB using wood pellets from standalone production plants; vi) micro-scale CHP using fuel cells (µCHP-FC); vi) micro-scale CHP using gas engine (µCHP-GE); and vi) micro-scale CHP using Stirling engine (µCHP-SE). The later three alternatives are assumed to use bio-SNG, which has large potential to substitute fossil gas in the existing and future fossil gas-based applications (Guerrini et al. 2013; Eisentraut 2010). Besides, solar water heating (SWH) integration is considered for each alternative and its installed capacities are determined based on optimization of the integrated energy system. The details of the considered electricity and heat production technologies are presented in Table 1.

In each alternative of heating, the selection of installed capacity for the main heat production unit is based on the minimum-cost approach of the yearly energy use. Besides, an electric resistance heater is used as a peak heat production unit to cover the remaining heat demand and also serve as a backup unit. Correspondingly, a buffer water storage tank (WST) of at least 10 lit/kW of peak heat demand is assumed for each configuration of heat production to regulate the fluctuation of heat use. In the heat production options integrated with SWH, the actual volume of a WST is optimized depending on the size of the SWH unit and the benefits of accumulated heat within the WST. Heat collected by a SWH unit was estimated based on solar irradiation, ambient temperature and fluid entering the collector (Kalogirou 2004). The hourly average global solar radiation and the ambient temperature for Växjö during 2013 (Swedish Meteorological and Hydrological Institute 2015) are used to estimate the solar heat gained by a SWH unit (Figure 2).

Table 1. Technologies for energy supply options

Technology & Equipment	Investment *(€)*	Add. initial cost *(€)*	Fixed O&M *(€/yr)*	Var. O&M *(€/MWh)*	Efficiency		Life time *(yr)*
					Heat	Elect.	
Heat production unit	*(/kW$_{heat}$)*	*(/unit)*					
• EHP[a]	1 770		400*/unit*		3.30[b]	-1.00	20
• WPB[a]	170	5000	6*/kW*		0.80	0.04	20
• µCHP-SE[a]	1 333			2.5	0.55	0.25	15
• µCHP-GE[a]	1 400			3.1	0.60	0.29	12.5
• µCHP-FC[c]	6 250			31.3	0.40	0.50	6
• µCHP-FC (2020)[c]	2 230			14.9	0.37	0.55	15
• SWH[c]	380		100*/unit*		500[d]	-11.9[e]	25
Hot water tank	(/lit)						
• WST-without SWH[f]	4.4						20
• WST-with SWH[f]	6.0						20
Electricity production	*(/kW$_{elect}$)*						
• BST[g]	1850		280*/kW*	3.47		46	25
• Wind mill[h]	2690			20.8		3700[i]	20
• Solar PV - micro[j]	1850[k]			34[l]		800[m]	25
• Solar PV - small[j]	1160[k]			34[l]		800[m]	25
Electricity delivery	*(/kW$_{elect}$)*						
• Network T&D[a]	165		5.0*/kW*[n]				45

[a] (Danish Energy Agency 2013); [b] average coefficient of performance (COP) for space and hot water heating; [c] (Danish Energy Agency 2014); [d] approximation of production (kWh/m^2), the actual value will be calculated; [e] electricity for solar pump and control, in kWh/kW panel; [f] (NIBE 2014); [g] estimated, based on (Danish Energy Agency 2014) and (Nohlgren et al. 2014); [h] (Nohlgren et al. 2014); [i] utilization time in hours/year; [j] (Nohlgren et al. 2014); [k] per kW$_{peak}$; [l] reinvestments of inverters and periodic overhauls (Danish Energy Agency 2014); [m] kWh production per year (Danish Energy Agency 2014); [n] assumption, 3% of investment cost;

The selected technology to deliver the building's electricity demand is based on the minimum-cost options among the renewable-based technologies considering all the costs associated with the production, T&D and delivery of electricity to end users. The coproduced electricity at end users, if any, is assumed to be balanced by the selected renewable-based power plants and is assumed to be equal to those coming from the grid in the calculation of costs and primary energy use. A distribution network loss of 8.3% is assumed for the delivered electricity, which is based on the average distribution losses during 2004-2013 in Sweden (Swedish Energy Agency 2015). Also, costs for the T&D network of electricity are considered (Table 2).

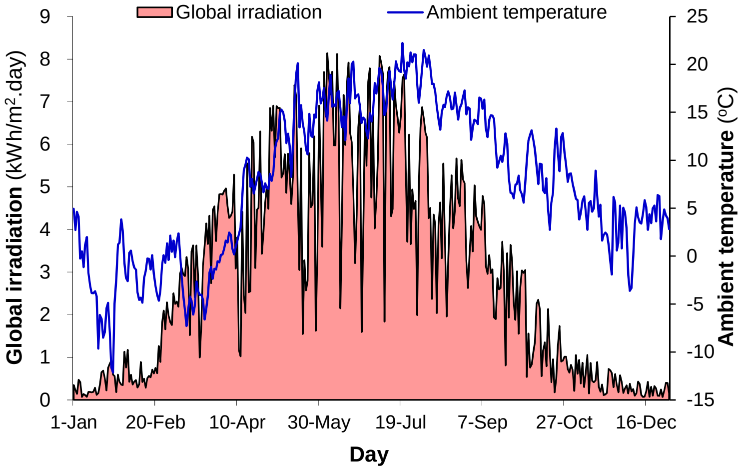


Figure 2. Daily global irradiation and ambient temperature in Växjö (2013)

All of the presented data were based on the lower heating value (LHV) of fuels and a discount rate of 6% is used for all the cost calculations. The energy cost estimations of biomass-based units were based on the 2013 wood fuel cost of €23/MWh (Swedish Energy Agency 2014). Costs and primary energy use of wood pellets for the local WPB are estimated based on standalone production plants (Truong et al. 2015). However, bio-SNG based on the second generation of bioconversion process using wood fuels is under development and demonstration. A study from International Energy Agency (Cazzola et al. 2013) showed that at low crude oil price, production cost of bio-SNG can be approximately 40.6 €/MWh. Therefore, this price level is used for the further calculation. The produced intermediate fuels at standalone plants are assumed to be delivered to final points of consumptions including T&D losses and costs of approximately 1.2% (Hagberg et al. 2009) and 6.0 €/MWh (Ravn and Engstrøm 2010) for the delivered wood pellets, respectively, and 3.9% (Steubing et al. 2011) and 9.7 €/MWh (Cazzola et al. 2013) for the delivered biogas, respectively.

3. Results

3.1. Electricity Supply Options

Table 2 provides the electricity production cost and fuel use for electricity production from different renewable-based technologies.

Table 2. Production cost and fuel use of electricity

Technology	Production cost *(€/MWh)*	Fuel use *(MWh$_{fuel}$/MWh)*
• BST	81.7	2.17
• Wind power	84.3	-
• Solar PV - micro	151	-
• Solar PV - small	104	-

A standalone power plant based on BST has a lowest electricity production cost of €81.7 per MWh. Electricity from of solar PV and wind mills has higher production costs with intermittent characteristics but fuel use is not required. A roof-mounted solar PV system at end-users could reduce T&D losses of produced electricity. However, when accounting the benefits of reducing T&D losses at 8.3%, this electricity production option is still less attractive compared to that from a distant BST power plant. Therefore, in the following sections, electricity from a BST is used as the reference for all the calculations.

3.2. Cost-optimal Heat Supply Options

Table 3 shows details of cost-optimal energy supply options for the two building versions. Here, total energy costs include all the production costs and related costs for the distribution and delivery of heat and electricity to the building.

Table 3. Cost-optimal energy supply options for the two building versions

Parameter	EHP	WPB	µCHP-SE	µCHP-GE
Existing version				
• Main heat production capacity *(kW)*	22.2	30.6	18.3	18.6
• Power connection capacity *(kW)*	58	40	45	43
• Fuel use at the local *(GWh/yr)*	-	170.1	230.2	213.0
• Coproduced electricity *(GWh/yr)*	-	-	40.48	43.43
• Purchased electricity *(GWh/yr)*	98.8	58.0	38.9	35.8
• Total energy costs *(€/yr)*	13 932	13 861	15 463	15 060
• Total primary energy use *(MWh/yr)*	241.8	312.2	323.7	297.4
Energy efficient version				
• Main heat production capacity *(kW)*	9.1	14.4	6.9	7.2
• Power connection capacity *(kW)*	34	25	30	29
• Fuel use at the local *(GWh/yr)*	-	71.7	87.7	82.1
• Coproduced electricity *(GWh/yr)*	-	-	15.42	16.75
• Purchased electricity *(GWh/yr)*	56.1	37.3	34.2	32.1
• Total costs *(€/yr)*	7 586	7 506	7 936	7 780
• Total primary energy use *(MWh/yr)*	137.3	163.1	171.4	160.8

The optimal installed capacity of the main heat production unit is approximately 37-62% compared to the peak heat demand of the existing building version. The corresponding value for the energy efficient building version is 27-56%. As a result, heat production for the peak heat demand is based on electric resistance heaters when heat demand goes beyond the capacity of the main heat production units. Electric resistance heaters cover 3.1-30% of the total heat demand, depending on the options.

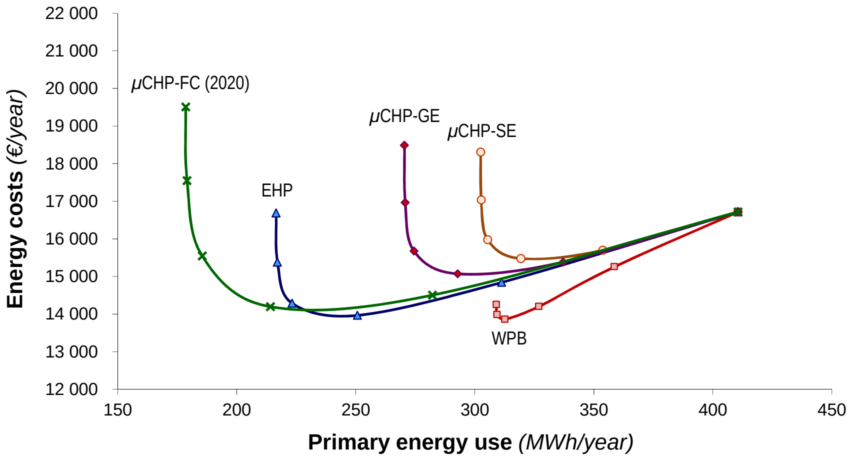
For both building versions, the heat production based on WPB is the most cost-optimal option. Also, a WPB at cost-optimal size produces 96.9% and 95.8% of the total heat demand in the existing building version and energy efficient building version, respectively. The option based on an EHP has almost the same total costs but lower total primary energy use compared to the WPB option. However, large power connection capacity to the power grid and high power consumption is desired. Options based on µCHP are generally costly but help to reduce power demand from the grid. The option based on µCHP-GE is more cost and primary energy efficient than that based on µCHP-SE.

A SWH is not cost efficient when used in combination with the considered heat production options except for the heating option using WPB. A SWH in combination with a WPB in a cost-optimal size has similar total energy costs but reduces total primary energy use. With a SWH unit of 13m^2 and 7m^2, fuel use of the boilers is reduced by 8.2% and 11.4% in the existing building version and energy efficient building version, respectively.

Of the considered options, a system based on a µCHP-FC is not cost efficient due to the high initial investment costs along with short service life time. However, unlike other technologies, technological performances and costs of systems based on fuel cells are expected to strongly be changed in the near future (Danish Energy Agency 2013; Danish Energy Agency 2014). Therefore, in the next section, a µCHP-FC based on projected performance and cost data of 2020 (Table 2) will be considered to elaborate the variation of cost and primary energy use of this technology in relation to the others. For the comparison, the presented cost data of this technology is also based on the fixed 2011 prices as similar to other technologies.

3.3. Variation of Costs and Primary Energy Use

Figure 3 shows costs and primary energy use of different energy supply options when the scales of the local heat production units are varied. Here, the scale of heat production by the main heat production units is varied to cover heat demand from a range between 100%, when the system is based 100% on the main heat production units, to 0% when the main heat production unit is eliminated and heat production is satisfied by electric heaters.



a) existing version

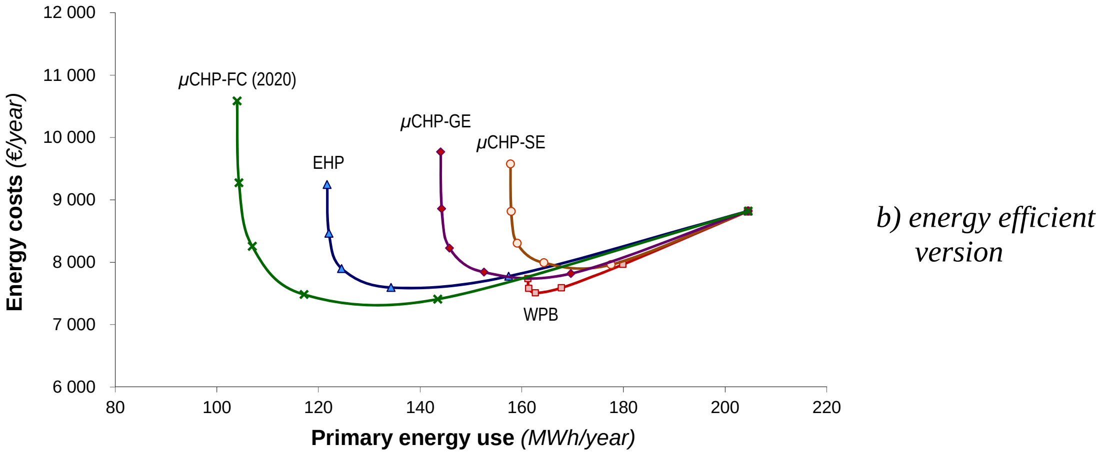


Figure 3. Energy cost and primary energy use of different energy supply options for the two building versions

Energy costs and primary energy use of a building are sensible with the installed capacity of heat production units. Options with a large main heat production unit satisfying 100% total heat demand have higher total energy costs. However, primary energy use is reduced due to the higher overall efficiency of heat production compare to electric heaters.

Of the considered options, the option using an EHP is primary energy efficient at a wide range of installed capacity even though its cost effectiveness varies. However, the option based on µCHP-FC using technology of 2020 showed an improved performance in term of primary energy use. Furthermore, this option is the most cost effective for the energy efficient building version.

4. Discussion and Conclusions

Technically, there are different renewable-based energy supply options for a building. However, cost and primary energy use of each option vary. Electricity from large biomass-based power plants is more cost efficient compared to that based on non-fuel technologies such as wind power or solar PV power plants. For the heat supply, a cost-optimal heat production option should not be based solely on a single heat production unit. A heat production unit which covers all heat demand is generally less cost-efficient than that which satisfies a major part of heat demand along with electric resistance heaters for peak heat demand. However, systems cover all heat demand gives lower primary energy use.

Energy demand of a building which influenced by its energy efficiency levels influence the cost-optimal scale of the local heat supply units. In a cost-optimal energy supply system, share of heat produced by the main heat production unit reduces with the reduction of heat demand. As a result, buildings with lower energy demand depends more on grid electricity if a cost-optimal energy system is targeted. Obviously, primary energy use and total energy costs for a building vary with the installed capacity of heat production units, which consequently influence the connected capacity and electricity consumption from the grid.

Of the considered heat production options, the option based on EHP proved to be the best cost- and primary energy efficient option. However, large power supply is required which creates a burden for the power grid. Also, performance of a ground-source EHP depends on the heat source as well as the demand of heating temperature. A system with low temperature heat demand may improve its performance, thus can strengthen its costs- and primary energy effectiveness. Besides, an option based on a WPB is cost efficient with higher system independent but is the most primary energy inefficient. Nevertheless, systems based on local micro-scale CHP units are costly even though they can be more energy system independent and improve primary energy effectiveness compared to heat-only boilers. In these CHP units, investment and O&M costs have strong impacts on economic viability. However, the projected performance of the micro-scale CHP system using fuel cell technology showed a high efficiency of primary energy and was cost competitive.

Non-fuel based technologies are less cost efficient than fuel-based ones. Electricity from wind mills and solar PV showed to be less cost effectiveness than that from biomass-based power plants. Also, the integration of SWH is not economically viable at the existing investment costs, fuel price and technical setups of local heating options. However, fuel use is reduced with heat production options integrated with SWH. Therefore, values of the reduced fuel use could be considered to offset the increase in the total energy costs to make such non-fuel based technologies viable.

In this study, the effects of system scales on investment costs are not considered. Also, technological performances and costs of technologies keep changing (Danish Energy Agency 2013; Danish Energy Agency 2014; Nohlgren et al. 2014) along with changed fuel costs. As a result, attractiveness of a technology may be changed and a cost- and primary energy efficient option of energy supply for a building could be changed. These aspects could be considered in further investigations.

This study demonstrates a trade-off between costs and primary energy use for energy purposes in an apartment building. Generally, a cost-efficient system requires more primary energy than an energy efficient system. Therefore, both the energy supply and demand throughout the year should be considered to optimize the cost and primary energy use of the energy supply options.

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