Expanding the horizons of power-to-heat: Cost assessment for new space heating concepts with wind powered thermal energy systems

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Abstract

Wind Powered Thermal Energy Systems (WTES) are the entirety of all conceivable combinations that consist of wind energy converters and thermal energy storage facilities. Although there is still a pressing demand for innovative technological solutions that allow the decarbonization of power and especially heat supply, comparative costs assessments that include the direct conversion of wind energy into heat are pending. In this paper, we conduct such an analysis for the first time. In particular, a techno-economic analysis based on the calculation of levelized costs of heat supply (LCOE) is presented. The novelty of this study is the comparison of five specific WTES concepts which either make use of electric boilers, hydro-dynamic retarders or heat pumps. The spectrum of applications considered ranges from heat supply for individual buildings to small villages and cities. The results show that LCOE below 5 c€/kWh can be reached. This indicates already competitiveness compared to conventional space heating technologies. In this means, we provide a systematic framework for future studies to evaluate the particular economic potentials of WTES in the energy market.

Keywords

Wind powered energy systems, wind energy, space heating, thermal energy storage

Abbreviations

AHP	Absorption heat pump
CAPEX	Capital expenditures
CF	Capacity factor
CHP	Combined heat and power
CSP	Concentrated solar power
EB	Electrical boiler
eHP	Electrical heat pump
LCOE	Levelized cost of energy (heat) supplied
mHP	Mechanical heat pump
OPEX	Operational expenditures
ORC	Organic rankine cycle
RET	Retarder
SCOP	Seasonal coefficient of performance
WTES	Wind powered energy systems

1 Introduction

1.1 Demand-oriented supply of renewable energy

Technologies for renewable energy supply, such as wind converters and photovoltaics, are not suited for generating power at any desired time. Given the growing demand for integration of low-carbon technologies into energy systems, the need to balance the variable availability of renewable energy resources is increasing. Frequently discussed solutions include, inter alia, power storage systems which, however, cause additional costs for construction and operation [1].

Wind turbines are nowadays one of the most cost-effective ways of generating electricity from renewable energy resources and thus can contribute significantly to low-carbon energy supply in the future. However, since the majority of wind turbines tends to provide power at the same time for a local spatial scale, a high supply of electricity is generated simultaneously [2] but not necessarily demand-oriented. Furthermore, extreme weather events pose the challenge to ensure security of supply with dispatchable generators, such as biomass-fired plants, over time periods in the range of weeks [3]. However, biomass resources are limited and can therefore only be exploited to a certain extent [4].

Similar to photovoltaic systems, wind turbines can be extended with energy storage systems in order to ensure a demand-oriented power generation. Still, commercially available large-scale storage technologies, such as pumped-hydro storage plants or compressed-air reservoirs, underlie spatial restrictions and can therefore only be installed if suitable site-conditions are given [5]. Opposed to that, energy storage technologies independent of location, such as lithium-ion or redox flow batteries entail relatively high investment costs if they are used as long-term storage [6]. The combination of both extensive location-independence and cost-efficiency can be provided by thermal storage systems [7]. However, so far, these storage facilities are only operated in concentrated solar power plants (CSP) for balancing the daily variability of solar energy [8].

1.2 Wind Powered Thermal Energy Systems

In conclusion, there exists a gap in the spectrum of renewable energy technologies for wind energy converters (WECs) that supplement energy supply at locations with low solar radiation at reasonable costs and in line with demand in terms of time and space. This gap can be filled by Wind Powered Thermal Energy Systems (WTES). WTES describes all combinations of wind turbines with thermal storage facilities for the demand-oriented supply of electricity or heat. Compared to existing power-to-heat solutions [9][10], the novelty of these concepts relies on the inclusion of on-site conversion of wind energy into heat. In particular, we define WTES as an innovative composition of state-of-the-art technologies, i.e. wind energy converters, thermal storage and, depending on the application, a thermal engine (Figure 1).

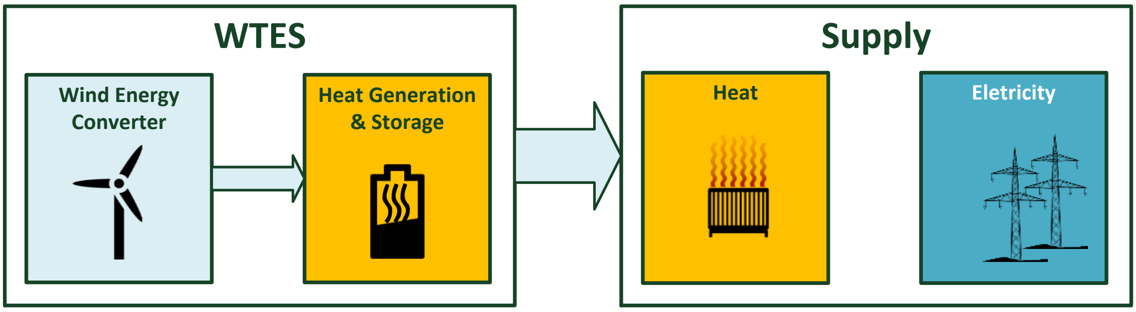


Figure 1: Basic concept of WTES

Due to their capability to work with high temperature heat, WTES can be potentially used for both heat and power supply. This ultimately results in a very broad spectrum of conceivable WTES implementation concepts. For example, WTES provide the opportunity for retrofit measures or the development of renewable alternatives to fossil-fired combined heat and power (CHP) plants. In this setup, WTES combine the systemic advantages of steam power plants (i.e. rotating mass) with the use of the renewable resource wind.

The central element of WTES is the thermal energy storage. Its purpose is to balance intermittent heat generation and demand. Available technologies are latent heat storage, thermochemical storage and systems for storing sensitive heat. Today's commercial systems store high-temperature heat in bulk materials made of natural materials such as granite or basalt with air as the heat transport and heat transfer medium. For WTES, the size of the storage is crucial since it defines possible operation strategies. Therefore, an appropriate dimensioning includes the consideration of temperature and performance range, the working medium and the required reaction times. For example, to keep losses for electricity reconversion with thermal engines low (Carnot efficiency), the thermal energy storage needs to work with high-temperature heat (>350°C). At this temperature power reconversion with efficiencies of up to 25% can be achieved by organic rankine cycle (ORC) processes [11].

Heat generation in WTES can be distinguished into direct and indirect energy conversion. The former is primarily based on the use of retarders for conversion of rotational energy into heat within a wind turbine. Technological realizations of retarders are on the one hand hydrodynamic retarders. Due to their broad application as truck brakes [33] they have considerably lower costs and weight compared to electric generators. On the other hand, induction retarders are similar to eddy-current brakes [12]. In addition to retarders, mechanical heat pumps can be used for direct energy conversion (compare section 2.1.1).

Indirect heat generation concepts still rely on electricity generation with a conventional generator and the subsequent conversion into heat. Theoretically, such concepts provide advantages with regard to the hybrid use of heat and electricity. For example, the principle of pumped-heat-energy-storage can be used in order to achieve the most efficient conversion between electricity and heat. The high-temperature heat is generated by means of electric heat pumps, which can result in a total efficiency of 54 % for the reconversion of electricity [13].

1.3 Wind Powered Thermal Energy Systems in the literature

With regard to the three major objectives for energy supply, i.e. economic efficiency, reliability and sustainability, possible WTES implementations are not yet sufficiently examined. Initial analyzes by [14] for a pure electricity generation concept show that electricity production costs of WTES are competitive with the ones of conventional wind energy converters extended by back-up gas turbines. Especially compared to wind-battery-systems, significant cost benefits are found. In the context of power-to-heat conceptions, other analyses emphasize the assessment of individual technical solutions which we interpret as sub-concepts of WTES. This especially applies to indirect heat conversion using electric heat pumps and boilers. Previous studies in this field concerning district heating supply in the Scandinavian region are frequently of system-analytical nature. For example, in [15] the objective is to ensure economically sensible system integration of a high proportion of wind power. There are only a few further scientific publications regarding WTES. A model-based study for direct heat conversion with vertical rotors and retarders is presented by [16]. Moreover, [17] propose the extension of CSP plants with wind energy converters. The idea of direct wind-to-heat-conversion is taken up in patents that either focus on the application of heat pumps [18] or hydrodynamic retarders [19,20].

Finally, a WTES research project for storing wind energy in a solid fuel storage tank at temperatures of around 600°C is carried out by Siemens Gamesa. The stored heat can generate 1.5 MW of electrical power via a steam turbine over a period of 24 hours. The researchers expect to achieve an efficiency of around 25 % at this early stage of development; a potential for efficiencies of 50 % in the future is expected [21].

In summary, at this state the technologies we refer to as WTES are in the conception phase. Although a broad variety of WTES realizations with state-of-the-art components is conceivable, a systematic assessment of cost structures of different WTES concepts and resulting energy production costs is still missing. This applies particularly for WTES concepts with direct heat conversion.

1.4 Objective

In this paper we present the first techno-economic comparison of different WTES applications. Thus, we lay the foundations for in-depth analyses of WTES concepts that are useful for low-carbon energy supply.

Our economic analyses focus on the heat generation path, as it uses commercially available components compared to power generation. Accordingly, we emphasize the comparison of different concepts for space heating with supply temperatures below 100° C.

First sufficient compositions of technical components to supply heat with WTES are identified. These systems are subsequently dimensioned for different heat consumption use cases and benchmarked against state-of-the art space heating technologies on the basis of an economic indicator, the levelized costs of energy supplied (LCOE). We deliberately chose a straight-forward-method for determining this indicator in order to identify those WTES concepts which are promising for a more detailed analysis. The appropriate setup for this examination is presented in the following chapter.

2 Methodology

2.1 Setup and assumptions

2.1.1 Considered concepts

For the conversion of rotational energy into heat we define five different setups according to Figure 2. Each of the heat conversion concepts is equipped with a generic heat storage unit. In this context, indirect heat generation by a conventional wind energy converter and an electrical boiler (EB) represents the reference case which is expected to be the most expensive WTES realization.

The advantage of applying a heat pump as heat converter is the potential to reach high efficiencies. Therefore, the second indirect heat conversion path is characterized by using electrical heat pumps (eHP). However, as compressors of eHPs are more or less rotating machines, the third heat conversion concept relies on directly driving a heat pump by coupling it to the shaft of a WEC (mechanical heat pump, mHP). Opposed to heat pumps, retarders are a mass product and thus imply low investment costs. Accordingly, the rationale behind direct heat-conversion and retarder-based WTES is cost-efficiency. This is due to the possibility to remove the electrical components from a WEC. Besides the exceptional application of a hydrodynamic retarder (RET), the combination of such a device with an absorption heat pump (AHP) allows for higher conversion efficiencies.

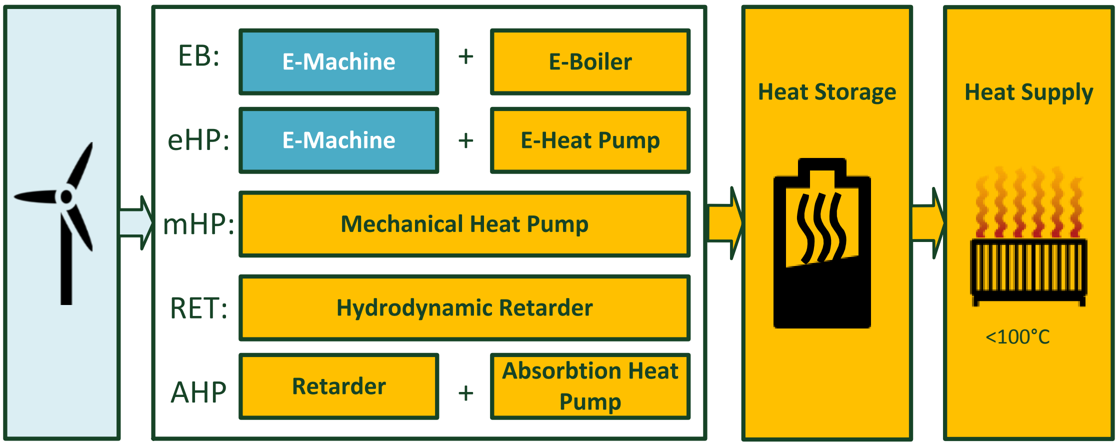


Figure 2: Considered heat conversion concepts for WTES dimensioned for space heating

2.1.2 System sizes and component dimensioning

To take into account economies of scale, we investigate three system sizes derived from typical heat demands of 1) a single family houses ("small"), 2) a small district heating network in a village consisting of 2000 inhabitants ("medium") and 3) a medium-sized district heating network in a city with 20,000 inhabitants ("large"). An additional criterion for the selection of particular system sizes is that energy supply is supposed to be in a range that can be covered by a small WEC, a single state-of-the-art multi-megawatt WEC and a wind farm, respectively. The resulting heat demand is based on a specific annual heat demand per inhabitant of 5.9 MWh [34] and checked against plausible ranges for this parameter. However, for reasons of simplicity this parameter is fixed for the following analyses of different system sizes. The resulting number and sizes of wind energy converters is varying according to the range given in Table 1. This is due to the fact that the rated power of WECs depends on the overall heat conversion efficiency of the individual WTES concepts as well as on site conditions (Table 1). We address the latter by varying the capacity factor from 0.1 to 0.35.

To estimate an appropriate size of the thermal energy storage we account for the number of hours to constantly supply a predefined peak load (Table 1). According to [34] this value is derived by multiplying the total annual demand with a factor of 0.000319 $^{1}/_{h}$. The latter factor results from a time series calculation as per [34]. The assumed number of hours to constantly supply the estimated peak loads are 2, 5 and 10 hours for the small, medium and large system setup, respectively.

Finally, in the case of large WTES setups, we exemplarily estimate the additional effort for heat transmission to identify how a remote windfarm serves the given heat demand. According to [22] a losses coefficient of 18.737 W/m is taken into account for this analysis.

System size	Used annual heat demand [GWh]	Thermal peak load [MW]	Rated power of wind energy converter(s) [MW]	Thermal storage capacity [MWh]
Small	0.023	0.008	0.005 – 0.027	0.015
Medium	11.8	3.764	2.5 – 13.47	18.8
Large	118	37.642	24.5 – 134.7	376

Table 1: System sizes in terms of annual heat demand, rated power of wind energy converter(s) and thermal storage capacity

2.1.3 Cost decomposition

Cost assumptions for different WTES concepts are summarized in Table 3 of the Appendix.

For each component of the WTES a cost break-down is conducted. Depending on the analyzed WTES concept, capacity specific capital expenditures (CAPEX) and operational and maintenance expenditures (OPEX) are reduced according to simplifications in the construction for WTES application compared to the commercial usage of the component. This applies especially to components of a WEC as in the case of direct heat conversion, electrical components, such as the electricity generator, transformer, and power converters are redundant. The cost-decomposition thus concerns primarily the CAPEX of the wind turbine. Based on [29] we estimate these costs to be 75 % of the total investment costs of a multi-megawatt WEC (see Table 2, Appendix). In addition, according to [23], we account for economies of scale by considering a reduction of 22% of CAPEX for WECs in a wind farm.

Furthermore, we consider a discount on CAPEX of mechanically driven heat pumps compared to their electrically powered counterparts due to the redundant electrical machine. Therefore, the following assumptions are made: Small WTES setups are considered to have one compressor which results in a fixed discount of 3,000 € representing the costs of one electrical machine. Electrical heat pumps applied to medium and large systems with a rated power greater than 2 MW are considered to have up to seven compressors [24]. One could account for the redundancy of the motors of these compressors by an appropriate expense deduction. However, since the number of compressors has a high impact on the efficiency of large heat pumps and due to reasons of simplicity these cost reductions are not considered for medium and large systems. Further CAPEX reduction potentials, for example concerning the tower (removing the electricity generator reduces the weight of the WEC's hub) are not considered.

With regard to OPEX the service and spare parts are influenced by the deduction of the previously mentioned electrical components. For WECs we therefore reduce the OPEX by 2%, whereas for heat pumps this discount is assumed to be 10%.

2.1.4 Efficiency accounting

Assumptions regarding conversion efficiencies of different WTES concepts that are applicable for the case studies on hand are derived from literature and are given in Table 3, Appendix.

Equally to the cost decomposition, conversion efficiencies are adjusted for WTES concepts where certain sub-components are deduced compared to the technical setup of commercially available devices. This applies to the electrical components of WECs and heat pumps resulting on the one hand in a total efficiency increase of 14% regarding small WECs and 2% in the case of multi-megawatt WECs. On the other hand the seasonal coefficient of performance (SCOP) for mechanically driven heat pumps is adjusted from 2.8 (used for electrical heat pumps) to 3.26 in the case of large systems and 2.92 for the rest.

2.2 Calculation of levelized cost of energy supplied

For the economic assessment and comparison of the different presented WTES concepts, a simple model in form of the following equation is used. Eq. (1) calculates the levelized cost of energy supplied (LCOE), i.e. heat, based on [30]:

$$LCOE_{ck} = \frac{\sum_{i=1}^{n} \frac{\sum_{j}^{\tau_c} I_{ijk} + M_{ijk}}{(1+r)^i}}{\sum_{i=1}^{n} \frac{E_{ck}}{(1+r)^i}} \qquad (1)$$

$$\forall c \in HC, \forall k \in S$$

where E_{ck}: annual heat generation with heat converter c for system size k

I_{ijk}: investment expenditures in the year i for component j and system size k

$LCOE_{ck}$: levelized costs of energy supplied of WTES with heat converter c for system size k

M_{ijk}: operations and maintenance expenditures in the year i for component j and system s system size k

$n = 20$: life time of the system

$r = 0.05$: discount rate

$S = \{small, medium, large\}$: set of system sizes

$\tau_c = \{WEC_c, HC_c, TES\}$: set of WTES components using heat converter c

With:

$HC = \{\mathrm{EB}, \mathrm{eHP}, \mathrm{RET}, \mathrm{AHP}, \mathrm{mHP}\}$: set of heat converters

TES: thermal energy storage

In this context, the appropriate investment expenditures are calculated based on the capacity specific CAPEX and the annual heat generation divided by the full load hours that result from a certain capacity factor. For example, for WECs this results in eq. (2):

$$I_{1,WEC_c,k} = CAPEX_{WEC,k} \cdot \frac{D_k/\eta_c}{8760\,h \cdot CF} \qquad (2)$$

$$\forall c \in HC, \forall k \in S$$

where CF: capacity factor

D_k: annual heat demand of system size k

η_c: conversion efficiency of heat converter c

Similarly to equation (2), the capacity specific OPEX of each component as well as the investment expenditures of heat converters and storage are calculated. CAPEX and OPEX for any required district heating network are not considered in the initial case of this analysis.

2.3 Sensitivity analysis and remote supply

The cost values used for the calculation of LCOE are taken from the literature (Table 3, Appendix). We refer to them as BASE scenario. To account for the uncertainty of considered CAPEX and OPEX, a sensitivity analysis is conducted. Therefore, two additional cost scenarios (HIGH and LOW) are estimated, resulting from assumptions for lower and upper cost boundaries for each component of a WTES (Table 4, Appendix). For example, in the case of heat pumps no discount for the deduced electrical machines is considered in the HIGH scenario. We are also aware of further uncertainties concerning additional cost for the integration of individual commercially components to a WTES. are likely to occur, such an estimation requires a technologically more detailed dimensioning of beyond the scope of this study.

With regard to heat transport from on-site generated heat to consumers, we exemplarily analyze the impact of this aspect for a large WTES setup. This is due to the fact that medium-sized and large systems need to transfer and distribute heat from a wind farm to a multitude of consumers. Therefore, it is more likely that additional losses and costs due to heat transport occur. Accordingly, we consider linearly increasing losses, CAPEX and OPEX for WTES concepts that rely on direct heat conversion. The rated power of WECs as well as the thermal storage size is adapted with respect to the transmission distance and the LCOE are modified for the last part of the following results section (Eq. (3)):

$$LCOE'_{c'}(d) = \frac{\sum_{i=1}^{n} \frac{\sum_{j}^{\tau'_{c'}} I_{ij,large} + M_{ij,large}}{(1+r)^i}}{\sum_{i=1}^{n} \frac{E_{c',large}}{(1+r)^i}} \quad (3)$$

$$\forall c' \in \{RET, AHP, mHP\}$$

$where$ d: distance

$\tau'_{c'} = \{WEC_{c'}, HC_{c'}, TES, DHN\}$:

set of WTES components inclusive heat transmissionusing heat converter c

With:

DHN: district heating network

However, opposed to this, indirect heat conversion concepts are assumed to use electricity transmission. Thus, all of the scenarios still involve an optimistic assumption since no expenditures for electricity transport infrastructure are considered and an existing electricity grid is supposed.

3 Results

In the following, three aspects regarding the resulting LCOE for the five different WTES concepts are analyzed. First, for the BASE cost scenario the LCOE is evaluated for different site-conditions indicated by the capacity factor. Second, ranges of the resulting LCOE are indicated for typical capacity factors between 0.15 and 0.25 taking into account the cost scenarios HIGH and LOW. Finally, also the effects of heat transport are shown for WTES concepts with direct heat conversion.

Concerning the structure of the remainder of this chapter, each sub-section consists of the presentation of results and explanation of figures followed by a discussion of the appropriate observations.

3.1 Base scenario

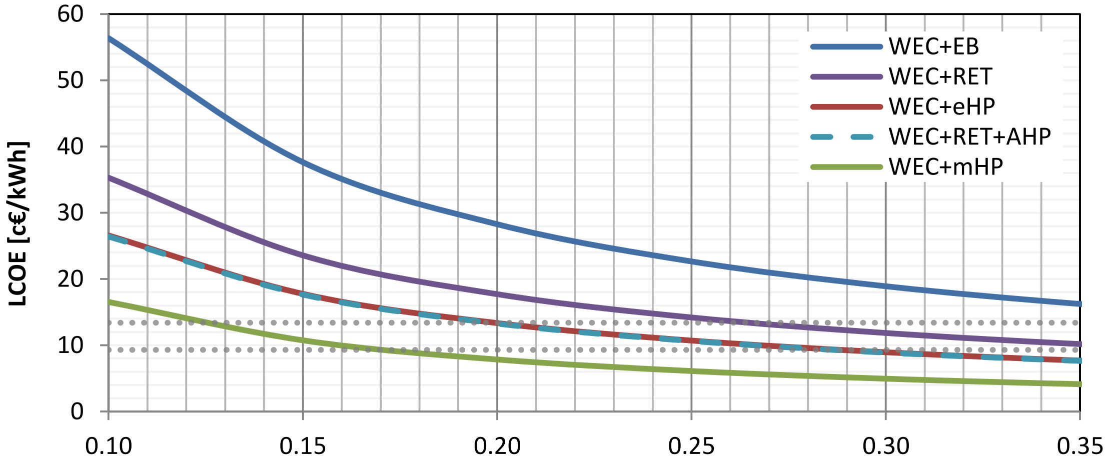
Figure 3 depicts the LCOE as a function of capacity factor of WECs for typical German sites for the three analyzed system sizes. The different WTES concepts are indicated by the colored lines. In addition, costs for heat production with conventional heating technologies are represented by dotted lines. In particular, for small systems these lines show costs resulting from an evaluation of the German heat market between 2012 and 2014 [35], while for medium and large system LCOE values are taken from [25] as benchmark[i]. For both the WTES concepts and the reference technologies district heating network costs are not included.

In Figure 3, all LCOE curves show a similar shape: While for capacity factors up to 0.25 a significant non-linear shape can be observed, for higher capacity factors it is approximately linear.

When comparing the LCOE curves for the different WTES concepts the following can be observed: With costs between 56.4 and 16.2 c€/kWh the reference WTES setup, represented by electric boilers powered by WECs, is the most expensive one for a single houshold. This holds also for both medium and large systems where the dark blue line in all subplots of Figure 3 is at the top. However, with regard to the former, for capacity factors greater than 0.23, the appropriate LCOE curve cuts the upper cost estimation for heat supply from wood-chip-boilers. In the case of heat supply for a city with 20,000 inhabitants this tipping point is already reached for a capacity factor of 0.19. Given site-conditions with more than 2700 full load hours (i.e. capacity factor of > 0.31), also the upper production costs with gas boilers are achievable.

Furthermore, the comparision of subplots in Figure 3 shows that there exists a fixed ranking of WTES concepts with regard to the resulting LCOE. This ranking is more or less independent of analyzed system size or site-conditions. Correspondingly, mechanical heat pumps directly driven by WECs appear to be the most cost effective WTES concept for heat supply, followed by systems that make use of electrical heat pumps, absorption heat pumps, retarders and electric boilers, respectively. Regarding the benchmark against conventional heating technologies this means, on the one hand side that the tipping points described above are reached the earlier the better LCOE-based ranking of a particular WTES concept is. On the other hand, for example at capacity factor 0.2, LCOE between 6.1 and 8.1 c€/kWh for heat supply by large WTES facilities with heat pumps already lie within the cost range of gas boilers.

Finally, for small systems two additional aspects can be observed. The LCOE-based ranking is less distinct since the red line representing the LCOE of electric heat pumps shows an equal slope as the light blue line indicating the same for absorption heat pumps. Moreover, especially in the case of low capacity factors, the spread of LCOE is significantly larger than for WTES concepts powered by multi-megawatt WECs (e.g. at capacity factor 0.1: 39,1 c€/kWh for small systems, but 8 and 5.4 c€/kWh for medium and large system, respectively). This also corresponds to the steeper slope of colored curves in the sub-plot concerning small systems.



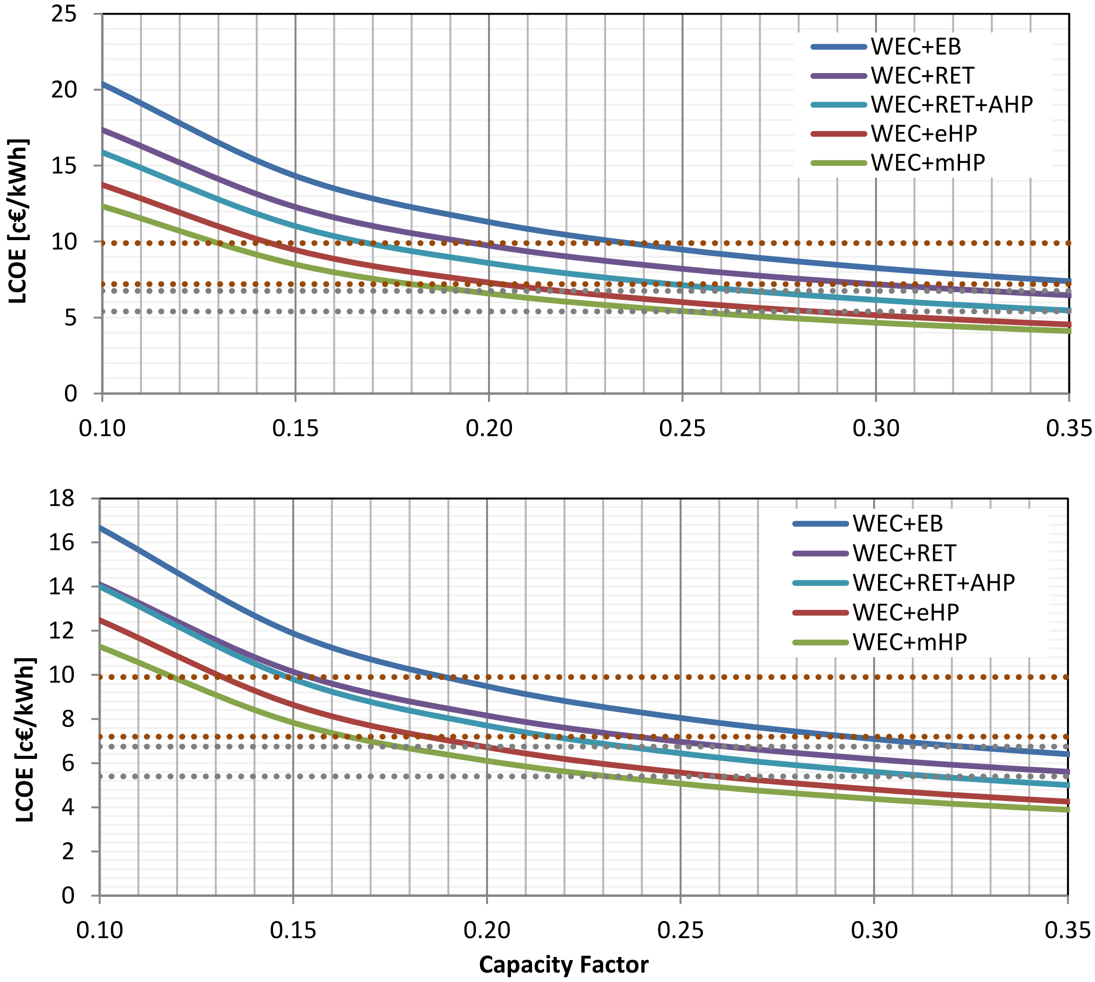


Figure 3: Levelized cost of heat supply for small (top), medium (center) and large (bottom) WTES systems, including reference LCOE for gas boilers (grey dotted lines) and wood chip boilers (brown dotted lines)

From the general shape of all LCOE curves the following can be derived: Regardless of the system size, due to the steeper slope for capacity factors below 0.2 the impact of site-conditions dominates the LCOE more strongly than in the case of higher capacity factors. For example, medium-sized, retarder-based WTES experience a LCOE reduction of 2.5 c€/kWh between capacity factor 0.15 and 0.20. Opposed to that, for an increase of capacity factor from 0.25 to 0.30 only a decrease in LCOE of 1 c€/kWh can be observed.

The decreasing costs over the three defined systems sizes are strongly influenced by the specific investment costs for WECs. The significant differences between small systems and their larger counterparts stem in particular from the initial CAPEX found in the literature. With a value of 6 €/MWh for small WECs these costs are nearly three times as high as in the case of multi-megawatt WECs. Opposed to that, the less significant differences between medium and large systems can be explained by economies of scale considered with reduction of 22% of WECs’ CAPEX.

With regard to the ranking of different WTES concepts it can be concluded that conventional, wind driven power-to-heat with electrical boilers is less cost effective. Rather, the SCOP introduced by heat pumps used as heat converters strongly influences the competitiveness in terms of cost efficiency for heat supply. The following example illustrated this: Although the CAPEX of heat pumps are 30 times higher than in the case of retarders (Table 3) the resulting LCOE of the appropriate WTES concepts are lower. This is due to the dominance of the CAPEX of the WECs (Table 3) which obviously can be significantly decreased if the total power conversion efficiency is improved by the application of heat pumps. Therefore, especially WTES with heat pumps show the highest potential to be competitive to traditional space heating with gas or wood chip boilers.

Finally, compared to medium and large WTES setups, the steeper cost decrease towards higher capacity factors implies that site-conditions are more crucial for small systems. This especially applies to capacity factors below 0.2 because in this area heat pump based WTES show a prominent potential to reach LCOE which are competetive with gas boilers. However, due to distinctly lower tower heights typical capacity factors for small WECs lie in a range between 0.12-0.22, opposed to 0.16-0.4 [30] for multi-megawatt WECs with tower heights greater than 100m for European sites.

3.2 Cost sensitivity

To better account for cost uncertainties caused by different site-conditions and assumptions for CAPEX and OPEX of each of the analyzed WTES concepts, Figure 4 depicts ranges for the resulting LCOE. The bar plots and error bars result from considering the HIGH and LOW cost scenario for conservative onshore site-conditions ranging between capacity factors of 0.15 and 0.25. This means, the upper bounds are derived from the HIGH cost scenario and a poor capacity factor 0.15, the lower bounds stem from the LOW cost scenario and a better capacity factor of 0.25. According to the findings from above, cost sensitivities are more prominent for small WTES setups. For these systems the mHP-based concept definitely shows the best performance as also in the worst case (capacity factor: 0.15, price scenario: HIGH) the LCOE are in the same area as the average LCOE values of the next more expensive WTES configurations.

For systems that make use of multi-megawatt WECs (i.e. large systems) the average LCOE over all WTES concepts is 8.3 c€/kWh with a standard deviation of 2.8 c€/kWh. If only heat pump-based configurations are considered these values become 7.3 c€/kWh with a standard deviation of 2.1 c€/kWh. More specifically, for the individual WTES concepts the ranges of LCOE significantly overlap each other, but still the ranking found above holds for worst case and best case assumptions. With around 10.5 c€/kWh for heat supply with mechanical heat pumps in large systems in the HIGH scenario, heat production costs lie above the typical price range for gas boilers and only the upper bound for heat supply with wood chip boilers is nearly met. However, seen from the other way round, in the best case (capacity factor: 0.25, price scenario: LOW) even the most expensive WTES configuration with electric boilers is able to fairly reach LCOE at the lower bound for heat supply with gas condensing boilers.

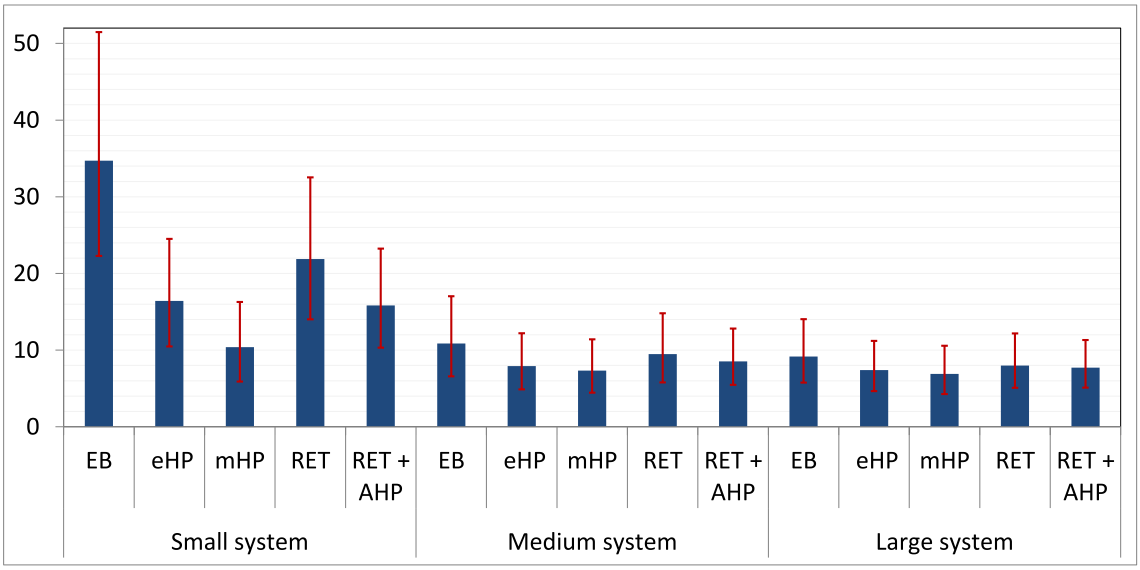


Figure 4: Ranges for LCOE for different system sizes and WTES concepts resulting from HIGH and LOW cost scenario and capacity factors between 0.15 and 0.25

The results for small systems show that not only the site-conditions are crucial for the cost-effectiveness of a certain WTES configuration, but also the choice between different WTES concepts implies large differences for the LCOE.

For medium and large system the results concerning the worst case depicted in Figure 4 suggest that in terms of production costs for heat supply a competitiveness of WTES compared to the benchmark technologies is not guaranteed. But still, the average LCOE especially of large systems with heat pumps show a high potential to be at least competitive to the carbon-free alternative relying on wood chip fired boilers. Furthermore, in the best case, even the LCOE of the more cost-efficient gas boilers can be undercut resulting in cost savings for an individual household of up to 270 € per annum (considered heat demand: 23,000 kWh, $LCOE_{mHP}$=4.3 c€/kWh compared to $LCOE_{Gas}$ = 5.4 c€/kWh). However, these potential cost savings strongly depend on possibly additional losses for heat transport between the wind farm and the heat consumer.

3.3 Impact of heat transport

Figure 5 exemplarily shows the LCOE for WTES configurations with mHP as a function of the distance between the windfarm and the final heat consumers. It is depicted by the green curves. While the upper one corresponds to the best case, the lower one represents the worst case regarding costs and wind site conditions (CF). Also for the benchmark heat supply technologies both an upper as well as a lower LCOE estimation is illustrated in Figure 5. These curves serve as a comparison in this sensitivity analysis and are not considered to depend on the distance. Thus, they are represented by parallels to the abscissa. Since the costs and losses caused by heat transmission are nearly independent of the considered heat generator, the LCOE-based ranking of WTES technologies presented above remains the same. For reasons of clarity, the distance dependent LCOE-curves for the other WTES concepts are therefore not depicted.

As Figure 5 shows, the LCOE estimations for gas and wood chip boilers are nearly completely within the shaded green area. This corresponds to the above mentioned finding that there is no guarantee to be more cost efficient than traditional technologies for space heating. But still, for distances up to 50 km, there is the potential for cost savings even if heat transport is considered. In Figure 5, this potential is graphically illustrated by the triangular surface that is created from the lower green and lower grey dotted line.

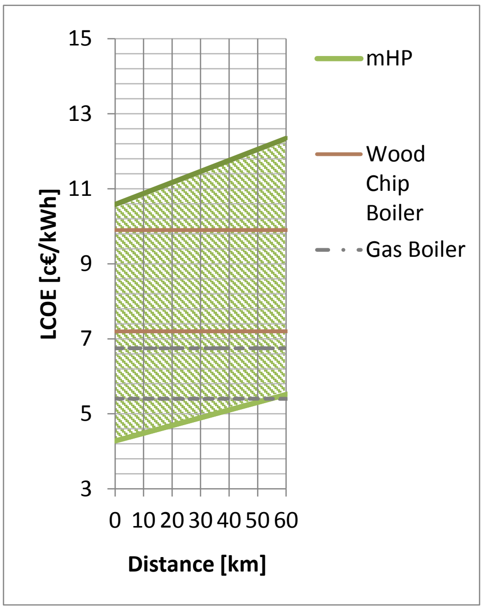


Figure 5: Comparison of LCOE considering heat transport in large WTES setups with mechanical heat pumps

The difference of LCOE over a distance of 50 km lies in a range of 1 c€/kWh (lower green curve) and 1.5 c€/kWh (upper green curve) for the mHP concept. Similar cost differences can be observed over all WTES concepts when the capacity factor is increased from 0.20 to 0.25 (mHP: 1.2 c€/kWh, eHP: 1.2 c€/kWh, RET: 1.2 c€/kWh, AHP: 1.3 c€/kWh, EB: 1.4 c€/kWh). In conclusion, it can be stated that the impact of heat transport on the LCOE is comparable to the influence of site-conditions within this range of capacity factors.

Considering that the mean capacity factor of newly installed WECs in Germany for 2016 is reported to be 0.31 (compared to an average of 0.19 over the last ten years)[26], it can be expected that also WTES that rely on direct heat conversion can become a cost-effective alternative to conventional heating technologies. This holds even though costs and losses introduced by heat transmission are taken into account.

When discussing the aspect of remote supply for all of the different WTES concepts, it needs to be noted, that in case of indirect heat conversion (by EB and eHP) it appears to be more cost-efficient to use electricity transmission rather than heat transport via a district heating network. This is not only due to the fewer losses. Even if it is assumed that no existing electricity grid can be utilized, it is more likely that the appropriate length specific costs (e.g. 150 €/m for three-phase medium voltage cables [27]) lie below their counterparts for district heating networks (Table 3, Appendix). Accordingly, it can be concluded that especially indirect heat conversion with heat pumps represents the most promising WTES concept for systems with high distances between WECs and heat consumption. However, further investigations are necessary to account for detailed costs involved by either electricity or heat transmission. For instance, this applies to CAPEX of length independent equipment such as compressors or substations.

4 Conclusion and outlook

In this paper, we analyzed the capability of Wind Powered Thermal Energy Systems (WTES) to provide space heat from a carbon-free resource. Compared to existing power-to-heat studies we conducted techno-economic assessment of different WTES concepts which use both direct and indirect heat converters. Therefore, only characteristics of commercially available components were taken into account. In particular, we evaluated the LCOE and identified a consistent ranking of WTES setups for different site-conditions and cost scenarios. We found that directly coupling a wind energy converter to a heat pump represents the most cost-effective WTES realization. Due to the negligible heat transport, this holds especially for small systems that are supposed to exclusively provide heat for a four-person household. For example, with around 2,400 € for space heating by WECs and mechanical heat pumps the average annual generation costs are less than one third of the costs associated with the use of an electrical boiler as heat converter instead.

We also analyzed larger system sizes that rely on the application of multi-megawatt wind energy converters. Here, concepts based on heat pumps performed in a similar manner since calculated LCOE bandwidths overlapped to a large extent. However, in large systems, for capacity factors above 0.25, also retarder-based setups performed well in comparison to two selected benchmark technologies for space heating, i.e. gas and wood chip fired boilers.

To account for additional costs and losses caused by heat transmission, we finally assessed wind farm-fed systems with regard to the distance between heat generation and consumption. It was found that even under such circumstances WTES can be competitive compared to established heating concepts. However, there is no guarantee to be more cost-efficient than these technologies since the LCOE strongly depend on the reachable capacity factor for certain WECs and site-conditions. Since concepts based on indirect heat conversion provide the possibility of electricity transmission, the WTES setup with electrical heat pumps appears to be the most promising for further investigations on large systems. Nevertheless, direct heat conversion concepts pose potentials for further cost reductions. This is due to the redundancy of the electric generator. If it is removed from the gondola the weight of the tower head can be reduced. An indicator for the associated CAPEX reduction potential can be derived from the difference of estimated costs for WECs with and without gears. Especially due to the higher weight of the synchronous machine in the latter the resulting total component costs of WECs with gears are approximately 7% lower [27].

Since the LCOE-based assessment shows the economic potential of WTES to be a competitive technology for space heat supply, two reasonable ways for further investigations are conceivable.

On the one hand, for future energy scenarios with high shares of renewable energy supply, the capability of WTES to provide demand-oriented heat as well as power enables an additional way of integrating the variable energy resource wind into the system. Applications can range from carbon-free CHP plants to hybrid power plants that integrate thermal heat storage facilities. Therefore, also power-to-heat-to-power concepts needs to be further examined assuming the availability of high temperature heat generation (Figure 6). Appropriate energy conversion pathways can be integrated into state-of-the-art energy system models. By treating uncertain WTES parameters, such as costs for high temperature heat converters as variables, such modeling exercises are useful to identify those WTES concepts and framework conditions under which this technology provides an added value to the energy system.

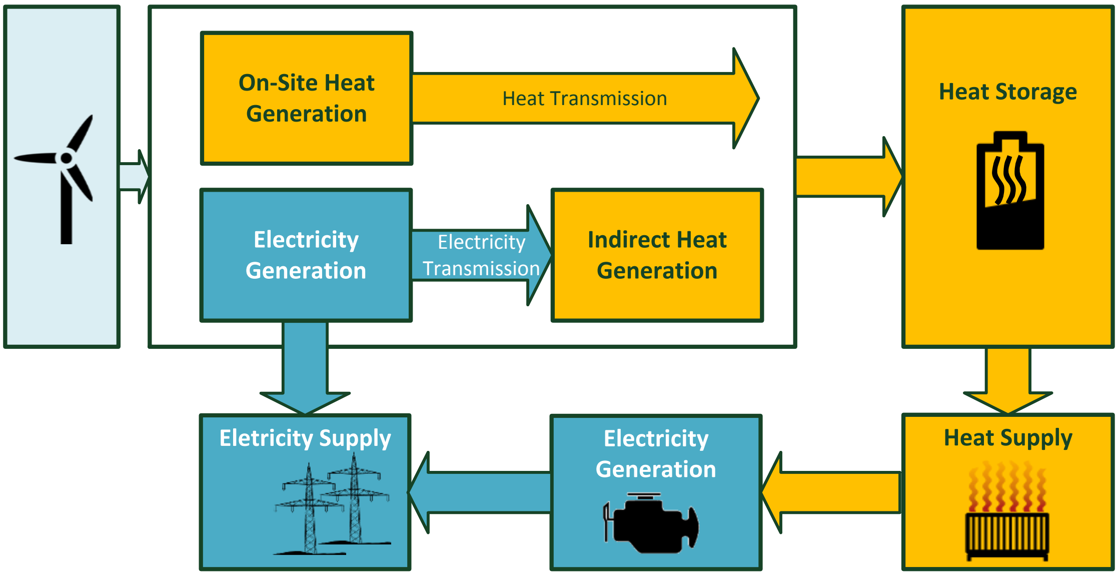


Figure 6: Overview of WTES concepts for heat and electricity supply

On the other hand, more detailed analyses especially of heat pump-based concepts for space heat supply enable a precise assessment of the economic feasibility of such WTES setups. Accordingly, a more sophisticated dimensioning and siting of the storage unit it is necessary to assess the trade-of between heat and electricity transmission as well as between central and decentral storage concepts. In this regard also the benefits and drawbacks concerning the placement close to heat generators or consumers play a role. Appropriate analyses require time series-based simulations that consider WEC tower heights and site-specific wind-speeds. With regard to the demand side, sector-specific heat consumption profiles provide the possibility to identify already existing markets for renewable heat supply with WTES. In particular, it can be expected that conceivable applications are sited at locations with comparably low solar radiation and limited access to biomass. To give an example for potential use-cases, low temperature heat driven processes, such as greenhouses, beer brewing or liquor distillation may be equipped with WTES in order to completely cover energy demand by renewables. In Germany, initiatives that are specialized on the utilization of solar energy for this issue are already licensed with the Solar® label [28].

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[i] Assuming an average exchange rate of 0.9 €/$, the associated heating costs with gas boilers lie in a range between 9.3 and 13.4 c€/kWh for a single household and between 5.4 and 6.8 c€/kWh for larger systems. In the case of wood-chip boilers the LCOE are reported in a range between 7.2 and 9.9 c€/kWh.

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Appendix

Multi-megawatt wind energy converter	
Component	Share
Tower	0.22
Rotor Blades	0.19
Rotor Hub	0.01
Rotor Bearings	0.01
Main Shaft	0.02
Main Frame	0.02
Gearbox	0.11
Generator	0.03
Yaw System	0.01
Pitch System	0.02
Power Converter	0.04
Transformer	0.03
Break System	0.01
Nacelle Housing	0.01
Cables	0.01
Screws	0.01

Small wind energy converter	
Component	Share
Turbine	0.37
Tower	0.31
Charge Regulator	0.04
Inverter	0.1
Cables and Switches	0.1
Installation	0.04
Grid Connection	0.03
Permitting	0.01

Table 2: Decomposition of total capital expenditures for small and multi-megawatt wind energy converters based on [29]

Technology	CAPEX [M€/MW]	$OPEX_{FIXED}$ [€/MW/yr]	$OPEX_{VARIABLE}$ [€/MWh]	η (SCOP) [-]	Ref.
Traditional WEC (< 5 MW)	1.97	-	20.00	0.93	[30]
WEC not for electricity generation					
With gearbox	1.77	-	19.60	0.95	
Without gearbox	1.56	-	19.20	1.00	
Wind farm (20-50 MW)	1.53	-	20.00	0.93	
Windfarm not for electricity generation					
With gearbox	1.38	-	19.60	0.95	
Without gearbox	1.21	-	19.20	1.00	
Small WEC	6.00	25,000	-	0.86	[31]
Small WEC not for electricity generation					
With gearbox	4.38	22,500	-	0.95	
Without gearbox	-	22,500	-	1.00	
Electric boiler	0.10	1,100	0.50	1.00	[32]
Electrically driven heat pump (eHP)	0.70	5,500	-	2.80	
Mechanically driven heat pump (mHP)	0.70	4,950	-	2.92 – 3.26	
Absorption heat pump (AHP)	0.40	18,500	-	1.70	
Retarder	0.01	250	-	1.00	[33]
	CAPEX [M€/MWh]	$OPEX_{FIXED}$ [%/yr]	$OPEX_{VARIABLE}$ [€/MWh]		
Small TES	0.023	0.7 %	-		[34]
Medium TES	0.011	0.7 %	-		
Large TES	0.009	0.7 %	-		
	CAPEX [€/m]	$OPEX_{FIXED}$ [%/yr]	$OPEX_{VARIABLE}$ [€/MWh]		
District heating network	200	1 %	-		[35]

Table 3: Cost and efficiency assumptions in BASE cost scenario derived from literature

	Cost scenario	CAPEX [M€/MW]	$OPEX_{FIXED}$[€/MW/yr]
WECs for electricity generation			
Small	HIGH	8.20	35,000
	LOW	6.00	20,000
Medium	HIGH	2.39	
	LOW	1.18	
Large	HIGH	1.86	
	LOW	0.92	
WECs for direct heat conversion			
Small	HIGH	5.99	31,500
	LOW	4.38	18,000
Medium	HIGH	2.14	
	LOW	1.06	
Large	HIGH	1.67	
	LOW	0.82	
Heat generators			
EB	HIGH	0.15	1,100
	LOW	0.06	1,100
HP	HIGH	1.004	7,300
	LOW	0.68	3,700
mHP	HIGH	1.004	7,300
	LOW	0.68	3,300
RET	HIGH	0.05	1,250
	LOW	0.01	250
AHP	HIGH	0.42	21,000
	LOW	0.37	16,000

Table 4: Differing cost assumptions for LOW and HIGH cost scenario compared to BASE