Energy Saving Potentials for Industrial Steam Boilers - Findings from the Ecodesign Process

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Abstract

Ecodesign is an important instrument of European energy policy making, which drives technological development and leads to significant energy savings by improving the environmental performance of energy-related products. Minimum energy performance standards and voluntary agreements which have been introduced under the Ecodesign Directive and so far concern more than 20 different product groups. One of the product groups currently investigated for possible regulation includes industrial steam boilers. According to estimates, industrial steam generation systems account for about one third of the overall industrial energy demand. Consequently, increasing energy efficiency in steam generation is relevant for suppliers, users and policy makers.

In this paper, findings from the Ecodesign Preparatory Study on industrial steam boilers are presented. According to the predefined methodology for energy-related products, steam boilers with different key characteristics will be defined as base cases. They differ in their thermal capacity, operating pressure and thermal efficiency. Based on a review of energy efficiency measures for industrial steam usage, relevant measures for industrial steam boilers will be identified. Then, the potential increase in thermal efficiency based on techno-economic design approaches for each base case will be estimated. Finally, a stock model will serve to quantify the overall economic energy saving potentials in Europe under differing policy scenarios.

We find that design improving options for industrial steam boiler are state of the art and established in market. Nevertheless, policy measures under the Ecodesign framework might increase the speed of their diffusion on the market. The resulting overall energy savings for the period from 2016 to 2030 would be 71 TWh.

Thus the results of this paper provide policy makers with an understanding of potential energy savings in Europe that would result from equipping new steam boilers with economic energy efficiency options within the Ecodesign framework.

Keywords

Ecodesign Directive, Steam Boiler, Energy Efficiency, Stock modelling, Technology diffusion

Introduction

In addition to the Energy Labelling Directive (EUROPEAN PARLIAMENT 2010) the Ecodesign Directive (EUROPEAN PARLIAMENT 2009) is one of the major policy instruments fostering energy efficiency within the European Union (Plötz et al. 2014). It establishes a framework for the setting of Community Ecodesign requirements for energy-related products with the aim of ensuring possible regulation of such products within the internal market. In order to investigate draft implementing measures for these products the European Commission carries out a series of analyses and assessments, which are called Preparatory Studies. The methodology of these studies is described in the Methodology for Ecodesign of Energy-related Products (MEErP).

The MEErP Methodology consists of 7 Tasks. Whereas Tasks 1 to 4 have a clear focus on data retrieval and initial product technical and market analysis, Tasks 5 to 7 have a clear focus on modelling. It is prescribed that Task 1 to 4 can be performed in parallel and Task 5 to 7 sequentially. The basic purpose of Task 1 is to define the product in the context of the Preparatory Study. Task 2 provides insight into the market status of the energy related product by gathering information on its production and trade data. Thus, within Task 2 the market volume and European stock of the product in scope is derived. Task 3 assesses the user behaviour. Within Task 4 the technical characteristics of the product in scope are introduced and efficiency improvement options/strategies are discussed. Based on the previous tasks so-called base cases are defined in Task 5 which represent a more or less “typical” product in the European stock and serve for further analysis. For these base cases different efficiency improvement options are assessed in Task 6. Finally, the effect of increasing the share of the assessed efficiency options in the market by means of the Ecodesign directive will be examined in Task 7 by drawing on specific policy scenarios. One of the product groups currently investigated for possible regulation includes industrial steam boilers with a thermal capacity lower than 50 MW. This paper presents findings from the Preparatory Study on industrial steam boilers as part of the Ecodesign process with the aim to quantify the possible impact of the directive on the energy savings in Europe for up to 2030.

The rest of the paper is structured as follows: First, the base cases are defined. Second, various efficiency options for these base cases relevant within the context of the MEErP are identified. An approach to quantify energy savings by prescribing the identified efficiency options within the framework of the Ecodesign directive is subsequently introduced. Finally the results are discussed.

Definition of base cases

The MEErP prescribes to define a set of so-called base cases. The basic idea is to quantify the environmental impact and especially the energy consumption of the product group in scope based on these base cases. As stated previously, these base cases are representative of typical products being used in the market of the European Union. The number of base cases should in general not be higher than ten. Consequently, the first step of the base case definition is to set a system boundary in order to sufficiently limit the scope of the product. An industrial steam boiler is usually embedded in a steam system within a facility. A steam system is basically categorized in a generation, distribution, end use and recovery system in practice (U.S. Department of Energy 2012). The industrial steam boiler is part of the generation system. The system boundary between the generation and distribution or recovery system might vary depending on the viewpoint. Nevertheless, engineering standards for industrial steam boilers indicate the system boundary applied in practice. Thus we set our system boundary based on the standards EN 12952 for water tube boilers and on EN 12953 for shell boilers[1]. The main components within the system boundary selected are illustrated in Figure 1.

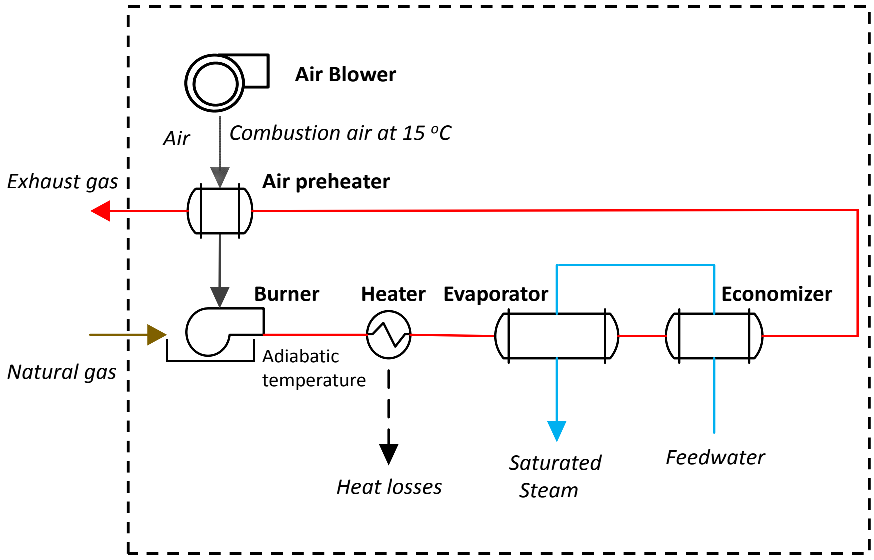

Figure 1 Main components within system boundary

[1] The EN 12952-1 and EN 12953-1 define in general those components belonging to the steam boiler assembly. EN 12952-15 and EN 12953-11 deal with acceptance tests. Fire-tube boilers are covered by the standard for shell boilers.

As can be seen, the components of the industrial steam boiler that are included in the scope of the Preparatory Study are the combustion system (air blower, burner) and the basic heat transfer equipment (evaporator, and optional economizer and/or air pre-heater).

The second step is to define the technical and operational key characteristics for the base cases. Together with the key characteristics the base cases should depict "average products" used in Europe as accurately as possible. Within this context it has to be stressed that the industries and thus the processes where steam boilers are applied differ from one another. For example, the processes range from applications where only heat is transferred to applications where heat- and mass is transferred such as in thermal separation processes. This heterogeneity makes the definition and setting of "typical" key characteristics difficult. Furthermore there is no comprehensive data or study available on the population of industrial steam boilers in the European Market. Given these boundary conditions the approach followed was to contact stakeholders representing steam boiler manufacturers. Thus we also discussed the purpose of the study during stakeholder meetings with the Association of the European Heating Industry (EHI), the representative European body of steam boiler manufacturers in Europe. The outcome of this discussion was the definition of key technical characteristics for each one of the base cases, such as the thermal capacity, operating pressure and thermal efficiency. Within this context the thermal efficiency is defined as follows:

$$\eta_{th} = \frac{\dot{Q}_{Steam}}{\dot{Q}_{Fuel}} \qquad (1).$$

In the above equation $\dot{Q}_{Steam}$ is the thermal duty that is delivered to the boiler feedwater stream for its conversion to steam of the desired properties (pressure, temperature). This thermal duty is also defined as the thermal capacity of the steam boiler. $\dot{Q}_{Steam}$ can be described by the equation:

$$\dot{Q}_{steam} = \dot{m}_w (h_{steam} - h_{feedwater}) \qquad (2).$$

In this equation, $\dot{m}_w$ stands for the mass flowrate of the feedwater/steam, whereas h_{steam} and $h_{feedwater}$ are the enthalpy values of the generated steam and the feedwater respectively. $\dot{Q}_{Fuel}$ is the original heat produced by the combustion of the fuel in the burner, based on its lower heating value. It is described by the equation:

$$\dot{Q}_{Fuel} = \dot{m}_{Fuel} LHV_{Fuel} \qquad (3).$$

In this equation, $\dot{m}_{Fuel}$ stands for the mass flowrate of the fuel and LHV_{Fuel} is the lower heating value of the fuel. Furthermore, the EHI provided us with sales data for steam boilers in clusters of different thermal capacities together with some best guesses on the share of sales of the products with a pressure below and above 16 bars for 2013. Assuming that characteristics of sales can be used to derive the characteristics of stock the key characteristics for the base cases were set as summarized in Table 1. Please note that these base cases only refer to gas or oil-fired steam boiler[2]. Please note additionally that the thermal efficiency listed for each base case assumes that the base cases are not equipped with any efficiency option to be evaluated in the following. This means that the values refer to a steam boiler only being equipped with an evaporator and no additional (efficiency increasing) heat exchanger such as economiser and/or air-pre-heater. Furthermore no efficiency improving control devices are incorporated.

[2] This decision was made based on information from industrial stakeholders guessing that more than 90% of industrial steam boilers in Europe are gas and/or oil-fired.

Table 1 Definition of base cases

Base case No.	Design	$\dot{Q}_{Steam.BC}$ [MWth]	η_{th} [%]*	Operational pressure [bar]	Steam production [t/h]
1	FT	2,5	87	15	3,2
2	FT	2,5	86	25	3,2
3	FT	7	87	15	9,0
4	FT	7	86	25	9,0
5	FT	20	87	15	25,8
6	FT	20	86	25	25,7
7	FT	35	87	15	45,1
8	FT	35	86	25	44,9
9	WT	35	85	15	45,1
10	WT	35	84	25	44,9
*: Without any design options; FT: Fire-tube; WT: Water-tube					

Energy efficiency options for industrial steam boilers

Identification of energy efficiency options for industrial steam boilers

Planning manuals, industry guidelines and scientific literature list various efficiency options for steam systems (U.S. Department of Energy 2012;United States Environment Protection Agency 2010;Therkelsen and McKane 2013;Einstein et al. 2001;Schult and Meyer 2013;Carbon Trust 2012). Within the context of the MEErP relevant options have to be filtered and selected. This is based on the fact that only certain measures can be fostered by any means of the Ecodesign directive as the directive clearly focuses on the **product** definition set in the Preparatory Study. Thus several measures which can hardly be modelled within these system boundaries had to be excluded from the study. An example is the blowdown heat recovery from blowdown water (Carbon Trust 2012). Additional measures that were excluded where those for which the effect of the efficiency improvement largely depends on the boundary conditions of the user application, as the Ecodesign directive sets requirements for manufacturer of steam boilers and not the end-users/customers. Such an example includes the automatic blowdown systems. These systems usually reduce the frequency of the blowdown heat recovery operation and thus the amount of the blowdown water, resulting in lower heat losses and thus lower annual fuel consumption (Carbon Trust 2012). Nevertheless the blowdown ratio necessary is determined by the feed water quality, which is within the scope of the customer. Thus the potential energy savings through this measure are strongly dependent on the operating conditions chosen by the customer leading to its exclusion from the Ecodesign directive. Finally efficiency measures having negative environmental side-effects were not examined in the study. This is because within the Ecodesign directive such measures and/or conflict of interests between different legislations should be prevented. This is for example the case by applying an air pre-heater in order to pre heat the combustion air by cooling the exhaust gas. Although the increase of the combustion air temperature is beneficial for the energy efficiency of the steam boiler, it can be detrimental in terms of pollutants (and especially NO_x) emissions. This is because the thermal NO_x formation is strongly dependent on the temperature of the combustion air (Schult and Meyer 2013). In fact, industrial stakeholders participating at the stakeholder meetings in Brussels[3] indicated that the application of an air pre-heater might lead to a trespassing of national NO_x emission limits. We consequently excluded the air-pre-heater from further analysis. So finally, only efficiency options fulfilling the following criteria were chosen for the Preparatory Study:

- The options must lie within the system boundaries set by the product definition.
- The options must not cause any direct negative environmental side-effects.

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[3] These meetings are foreseen to incorporate stakeholder from industry, NGOs, standardisation bodies etc. by the MEErP.

The options chosen for further analysis are the following:

- Economiser (ECO): An economiser preheats the feed water by cooling down flue gases via a heat exchanger. Thus it increases the overall thermal boiler efficiency by reducing heat losses and subsequently the fuel consumption.
- Combustion Control (CC): This measure refers to the implementation of an automatic control system for determining the flowrate of the combustion air. In the case of complete, i.e. perfect combustion gas or oil would burn stoichiometrically so that no oxygen would be existent after combustion. This is in practical applications not the case as some of the oxygen is left over in the flue gas. One reason is that since the condition of air isn't always the same, burners without O_2 correction have to be set to cover most unfavourable weather conditions – ensuring that every molecule of fuel is completely burned off. An automatic control system uses the measured O_2 and CO content in the exhaust gas as input. The aim is to adjusts the volume of the combustion air in the way that excess air in the flue gas is being minimized (O_2 correction, addressing real life burner configurations). It furthermore guarantees that CO-thresholds are not trespassed (CO-measuring). Thus it minimizes heat losses through excess air in the flue gas and increases the thermal efficiency of the steam boiler (Schult and Meyer 2013).
- Variable Speed Drives (VSD): Operating a steam boiler at part load requires less combustion air and thus a lower speed of the fan compared to full load operation. When the electric drive is not equipped with a frequency converter the volume of sucked-in air is regulated by air dampers. When the drive for the air blower is equipped with a frequency converter the speed of the drive can be adjusted to the needs of the load of the steam boiler. Thus, a frequency converter saves electrical energy compared to regulating with air dampers (Schult and Meyer 2013).

Impact of energy efficiency options on base cases

The energy savings of the above chosen efficiency options deviate among real-life industrial steam boilers. They are influenced by various factors such as the thermal capacity of the industrial steam boiler and/or its operational behaviour. Given a fixed number of base cases, only indicative values for the energy savings can be assumed for further analysis. Based on consultations with industrial stakeholders we assume the following values for the ECO and CC (independent of load situation):

- By equipping each base case with an ECO the thermal efficiency increases by 5.5 percentage points.
- By equipping each base case with CC the thermal efficiency increases by 1.75 percentage points.

The energy savings, which result from, ECO and CC are then a direct result of the saved fuel by increased thermal efficiency. For the VSDs the relative savings compared to the alternative of regulating the mass flow of combustion air by dampers have to be considered. Therefore, firstly the required power needed at the shaft for the blower is estimated. Then the appropriate electric motor size according EN 50347 for each base case (J.P. Arning et al. 2009) is chosen. The resulting energy savings are the difference between the power needed at full load and the power needed at 75% load (as by damping regulation always full load power is provided). The assumed relative savings are shown in Table 2.

Table 2 Energy savings VSDs

Base case No.	Output Power [kW]	Assumed efficiency of drive (weighted for stock)	Power demand at average load with throttle [kW]	Power demand at average load with VSD [kW]	Relative savings [kW]
1-2	1,5	0,78	1,9	0,8	1,1
3-4	5,5	0,85	6,5	2,7	3,8
5-6	22,0	0,90	24,5	10,3	14,2
7-10	45,0	0,92	49,2	20,7	28,4
assumed average load = 75%.					

Long-term impact and scenarios

Modelling of stock and technology diffusion

According to Hirzel et al., "Stock models can serve as means to describe and analyse the structure of energy demand. They are mathematical descriptions of how objects or sales build a stock of objects or products over time. As a general rule of stock modelling, the size of a stock of objects within a system is characterised by four parameters: the number of objects entering and leaving the system and the number of generated and destroyed objects within the system." (Hirzel et al. 2012).

Hirzel et al. (2012) also present two widely used approaches to develop a stock model. One of the two approaches requires the age distribution of the stock under consideration in a specified year (i.e. starting year) and the number of objects in stock for the same year. The stock is then built over time by considering that the objects in stock age with every time step. Objects are removed from stock (leaving) over time depending on their age with a certain probability. The starting year can be the present year, so that the present age distribution is required for this approach. The second approach is based on historical sales data for the object in scope for many years before the present year. The stock for the present year is then basically built by assuming that with a certain probability the former sales are scraped at a certain age or vice versa that with a certain probability the former sales survive in stock. The difference compared to the first approach is that the age distribution of the stock is at any time a result of the assumed survival probability at certain ages. The survival probability can be described by mathematical functions such as weibull functions or simple stepwise functions.

For the Preparatory Study no age distribution for any year of industrial steam boilers had been given. Furthermore, no sales data on many early years (before the present year) has been given. In fact, the only indication to build a stock model has been sales data for 2013 and a best guess estimation of the current stock by the Federal Industrial Association of Germany House-, Energy and Environmental Technology (BDH) for Europe. Given these boundary conditions, we proceeded with the second approach as presented above. To fill the data gap on the sales for many early years we use an approach based on economic figures. The total stock of steam boilers $M(t)$ in year t is then: $M(t) = \sum N(u) \cdot L(t-u)$ (4),

where $N(u)$ denotes the sales in year u and $t-u=a$ represents the age of the boilers in the year *t*. $L(a) = 1 - F(a)$ is then the survival function describing the evolution of remaining objects. As the data is uncertain for the past, we proceed with a simple stepwise survival function so that $F(a)$ is defined as follows: $F(a) = \begin{cases} 1 \text{ for } t > 25 \\ 0 \text{ for } t \leq 25 \end{cases}$ (5).

The sales are then calculated from 2013 25 years backwards for every year by assuming that sales of industrial steam boilers are coupled with GDP growth of the European Union (EU-28). The assumed sales for the period from 1988 to 2012 are back casted as follows:

$$GDP.GR_{u+1} \geq 0 \Rightarrow N(u) = \frac{N(u+1)}{(1 + GDP.GR_{u+1})}$$
$$GDP.GR_{u+1} < 0 \Rightarrow N(u) = \frac{N(u+1)}{(1 - GDP.GR_{u+1})} \quad (6),$$

with $GDP.GR_u \in [-1,1]$ for $1988 \geq u \leq 2013$. In this equation $GDP.GR_u$ is the annual growth rate of the GDP in the EU 28 for the year u. This calculation is carried out for every base case. The result is a stock of steam boilers with an age distribution for every base case in the year 2013. The sales for the period from 2014 to 2030 are estimated by using the following equation:

$$N(\text{u}+1) = N(\text{u}) \cdot (1 + GDP.EGR_{u+1}), \text{with } GDP.EGR \in [0,1] \quad (7),$$

for $2014 \geq u \leq 2030$. In this equation $GDP.EGR_u$ is the estimated growth rate for the GDP in the EU 28 for the year u.

A constant growth rate of 1.5% for the whole time period is assumed. This calculation is conducted for every base case and then the figures are rounded to integers so that the notation is as following for the further analysis: $M_{BC}(t) \sim M_{BC,t}$. The resulting assumed sales are presented in Figure 2.

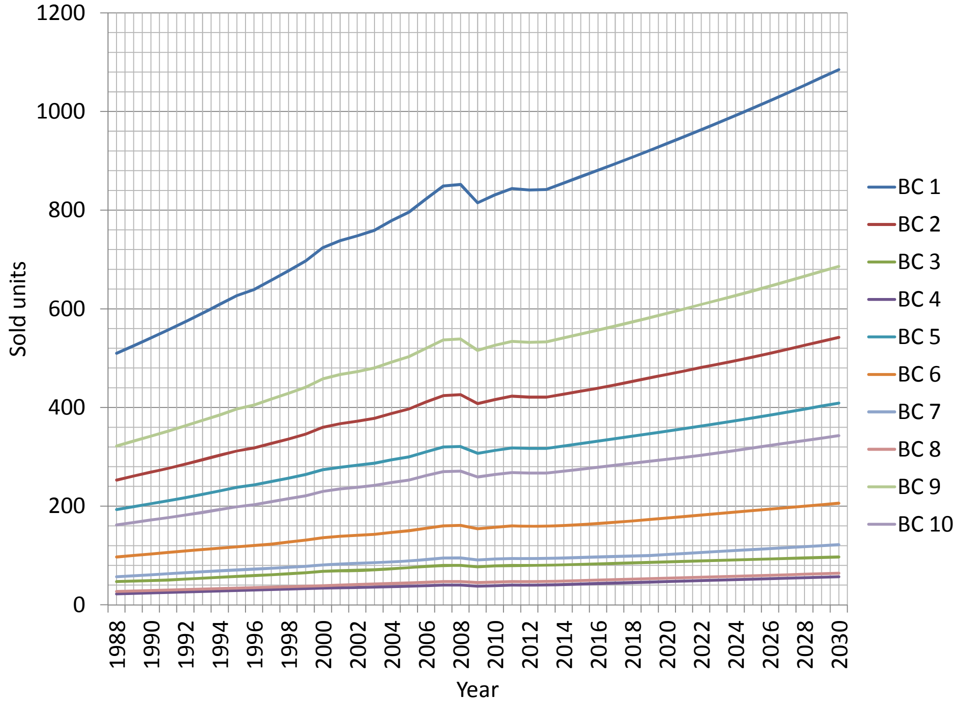

Figure 2 Assumed sales per base case

The resulting stock is presented in Figure 3. This stock of steam boilers is the basis for any further analysis. Please note that we do not address sales before 1988 so that considerations based on the stock presented can be only made for 2013 onwards.

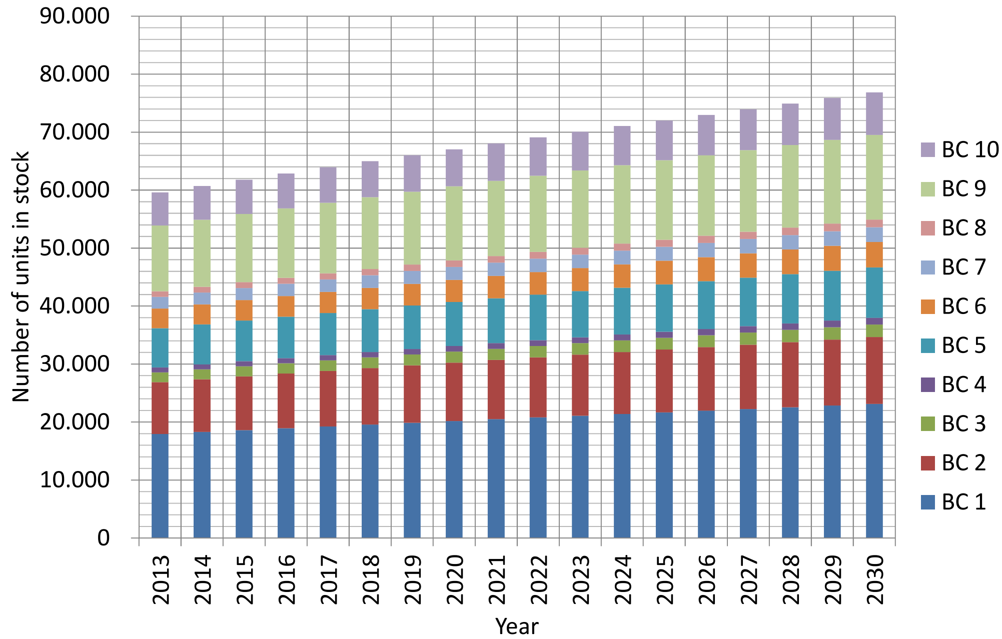

Figure 3 Assumed stock per base case

In order to evaluate how much energy can be saved by means of the Ecodesign directive it has to be estimated how the chosen energy efficiency options could be adopted by customers in the future (i.e.

future sales) omitting any fostering by means of the Ecodesign directive (i.e. policy mechanisms). Thus, a model to anticipate the diffusion of the design options is necessary. Within the literature on new technology diffusion there are several models which describe the adoption of new technologies among users. The so-called epidemic and probit models are the most common (Geroski 2000). The probit model follows "the premise that different firms, with different goals and abilities, are likely to want to adopt the new technology at different times". The epidemic model "builds on the premise that what limits the speed of usage is the lack of information available about the new technology, how to use it and what it does" (both quotes from Geroski 2000). No data on the different goals and abilities of firms which buy industrial steam boilers has been available for our study. As a consequence we model the diffusion of the design options based on ideas from epidemic models. Within epidemic models two main approaches of describing the diffusion of new technology are present. One common approach leads to the central source model, where the knowledge about the existence of a new technology among potential users drives the adoption of the technology. Within this model the number of users over time is described with an exponential function. The other common approach is based on so-called word of mouth communication. In this model the underlying idea is that when new hardware is adopted so-called software[4] knowledge is built by using the technology. It is then supposed that existing users contact non-users independently and with a certain probability infect the non-user to adopt the new technology. Furthermore, a maximum number of users is assumed. The number of users at any time is then dependent on the number of users which have already adopted the new technology, the number of users which still could adopt the new technology and the probability with which non-users contact users. This leads to a function where the "population of users gradually rises, increasing the aggregate stock of software information that can be passed on until it hits a maximum and then it declines (as non users get increasingly hard to find, therefore, to infect)" (Geroski 2000). This function is a logistic function which has a characteristic S-shape. Our premise is that the technology diffusion for the chosen design options follows the word of mouth approach. We consequently assume that the percentage of sales that is equipped with the appropriate design options can be described by a logistic function with a characteristic S-shape.

The EHI provided estimations on the share of sales which are equipped with ECO and CC for the years 1993 and 2013 (Table 3). We furthermore made own estimations on the share of sales equipped with VSDs. Finally, we assume maximum diffusion rates (based in technological restrictions) for each design option as described in Table 3. Together with the previously mentioned assumption on the characteristic shape we derive characteristic S-curves for the design options representing the share of sales equipped with the options over time. These curves represent the autonomous (business as usual, i.e. Autodiff) market diffusion scenario (cf. Figure 4).

Table 3 Assumed share of sales for chosen design options

Technology option	**Market share [%], 1993**	**Market share [%], 2013**	**Maximum diffusion [%]**
Economizer	50	80	100
Combustion control	13	60	100
Variable speed drives*	5	50	100
* Own assumptions (not from BDH).			

[4] Within the context described above software knowledge is knowledge about a new product which is being mainly built up by using the product. For industrial goods this can for example be operational experience.

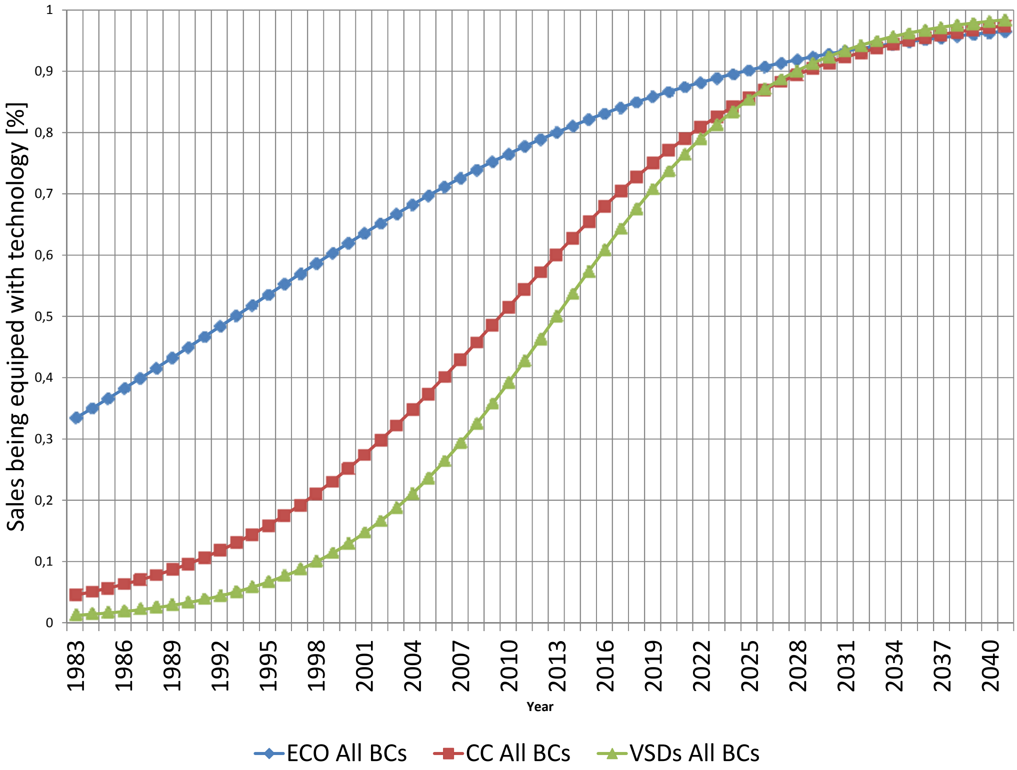

Figure 4 Assumed S-curves for chosen design options

Scenario analysis

The goal of the scenario analysis is to estimate which energy savings can be achieved by means of the intervention through the Ecodesign directive up to 2030 compared to an autonomous development of the steam boiler market. There are basically two mechanisms in the Ecodesign directive which intend to foster the diffusion of energy-efficient technology among energy-related products. Within the framework certain implementing measures can be prescribed. An exemplary measure is to set so-called Minimum Energy Performance Standards (MEPS) for products in scope. For an industrial steam boiler such measure could result in minimum energy efficiency standards for products sold. Furthermore, the directive provides the possibility for voluntary agreements or other self-regulation measures. Within this framework industry associations or comparable bodies might proceed to self-regulatory actions with the goal of increasing the energy efficiency of new manufactured products. However, these initiatives have to fulfil certain criteria presented in Annex VIII of the Ecodesign directive. Criterion 3 on representativeness requires that the "Industry and their associations taking part in a self-regulatory action must represent a large majority of the relevant economic sector, with as few exceptions as possible" (EUROPEAN PARLIAMENT 2009, Article 15). As only a few manufacturers[5] responded to the surveys carried out within the Preparatory Study and only two manufacturers participated at the open held stakeholders meetings in Brussels a self regulatory

[5] Please note that in Task 2 main EU manufacturers of industrial steam boilers were identified and invited to participate in a survey with the aim to collect market data. The manufacturers were also requested to register as stakeholder and to attend the stakeholder meetings. In sum 24 manufactures had been addressed (cf. page 95 of the final report). Two manufacturers participated at the meetings. The participating manufacturers were Bosch Industriekessel GmbH and Viessmann Werke Berlin GmbH. Bosch Industriekessel GmbH was represented by Mr. Joachim Lenz in the first stakeholder meeting and additionally Mr. Paul Köberlein in the second stakeholder meeting. Viessmann Werke Berlin GmbH only attended at the first stakeholder meeting and was represented by Mr. Markus Pieper. For further participants please refer to the corresponding Minutes of the meeting published on the project website.

initiative might be unrealistic. Thus self-regulatory initiatives for further analysis in the context of this paper[6] are omitted.

As already mentioned, one possibility for an implementing measure might be to apply an MEPS for industrial steam boilers. However, this would have to at least need to address the pressure level and type of applied fuel in a proper way. This is based on the fact that these factors determine the maximum efficiency possible for industrial steam boilers by using state of the art technology. Bearing in mind that customers operate industrial steam boilers differently at various part loads during a year, the part load behaviour should also be subject of an MEPS for industrial steam boilers. Due to the lack of data (operation hours) and the heterogeneity of the design configurations (i.e. the application of different fuels and pressure levels) the setting of an MEPS requires an in-depth technical analysis of the many different cases to set adequate thresholds for each one. As a result, another approach within the possibilities of the Ecodesign directive is followed. An implementing measure prescribing mandatory design features for industrial steam boilers is assumed. From the presented design options we consider equipping industrial steam boilers with an Economiser (ECO), Combustion Control (CC) and Variable speed drives (VSD) to be mandatory. This is based on the fact that from the techno-economic analysis for the chosen design options we conclude the options to be cost effective in terms of customers' Life-Cycle-Cost[7], not to be technically restricted in any case and not causing any negative environmental side effects. As a consequence we model two scenarios where we forecast the energy consumption of industrial steam boilers based on the assumptions listed in the following:

- **Autonomous diffusion (Auto diff):** it assumes the increase of the percentage of new sales equipped with the design features ECO, CC and VSD to follow fitted S-curves (as in Figure 4).
- **Ecodesign diffusion (Ecodesign diff):** it assumes the design features ECO, CC and VSD to be mandatory for every new steam boiler sold from 2016 onwards.

We then derive the energy consumption per scenario, per year by first forecasting the market share of the design options per technology, per year for each scenario. For the Auto diff scenario the market share follows the fitted S-curves as presented in the foregoing section. For the Ecodesign diff the market share is simply 100% for the chosen design options from 2016 onwards representing the mandatory implementing measure. The market shares for the evaluated time frame from 2013 to 2030 are presented in Figure 5.

Keeping in mind that machines are being replaced after an age of 25 years the share of each technology in stock can be calculated, as the prediction of sales and the age structure of the current stock is given. The technology share is then:

$$TS_{BC,A,t} = \frac{EQ_{BC,A,t}}{M_{BC,t}} \quad (8),$$

where $TS_{BC,A,t}$ is the technology share of technology A for the base case with number BC in year t, $EQ_{BC,A,t}$ is the number of Machines in year t of base case with number BC being equipped with technology A and $M_{BC,t}$ is the total number of machines of base case with number BC in year t. In order to evaluate the thermal energy consumption of the steam boiler stock for each base case a weighted stock efficiency is being calculated based on the technology shares mentioned above. As we model two technologies increasing the stock efficiency A is replaced with ECO for the economizer and with CC for the combustion control. The weighted stock efficiency per base case is then:

$$\eta_{BC,t} = \eta_{BC,o} + (TS_{BC,ECO,t} \cdot EI_{ECO}) + (TS_{CC,BC,t} \cdot EI_{CC}) \quad (9),$$

where EI is the thermal efficiency improvement for the appropriate technologies and $\eta_{BC,o}$ is the efficiency of base case with number BC without any technology option (as in Table 1). The thermal energy consumption for the whole stock is then derived as follows:

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6 In our study published at www.eco-steamboilers.org we also model and present an approach to estimate energy savings by a voluntary agreement.

7 This analysis has been made in the Preparatory Study. Please refer to the report on Task 6 published at www.eco-steamboilers.org for further information.

$$EconT_{BC,t} = \frac{M_{BC,t} \cdot O_{BC} \cdot \dot{Q}_{Steam.BC}}{\eta_{BC,t}} \quad (10),$$

with $\dot{Q}_{Steam.BC}$ as described in the definition of the base cases and O_{BC} is the operation hours per year, BC indicates the number of the base case. Differing thermal energy consumptions values per year for the different scenarios consequently result from different weighted stock efficiencies for the scenarios. For the electricity consumption we only calculate the electricity consumption of the air blower (according to the pre-defined system boundary). Therefore, we take an average part load for the whole stock and the number of VSDs in stock into account. We calculate the electricity consumption (*EconE*) caused by the boiler for the stock as follows:

$$EconE_{BC,t} = M_{BC,t} \cdot O_{BC} \cdot P_{BC} \cdot (1 - TS_{VSD,BC,t}) + M_{BC,t} \cdot O_{BC} \cdot P_{BC} \cdot TS_{VSD,BC,t} \cdot (APL_{BC})^3 \quad (11),$$

where P_{BC} is the power needed at full load and $APL_{BC} \in [0,1]$ is the assumed average load for base case with the number BC. In our scenarios APL_{BC} equals to 0.75 for all base cases. Finally, the electricity consumption is converted to primary energy assuming a conversion factor of 2.5. The operation hours are assumed to be 1250 for all base cases per year[8].

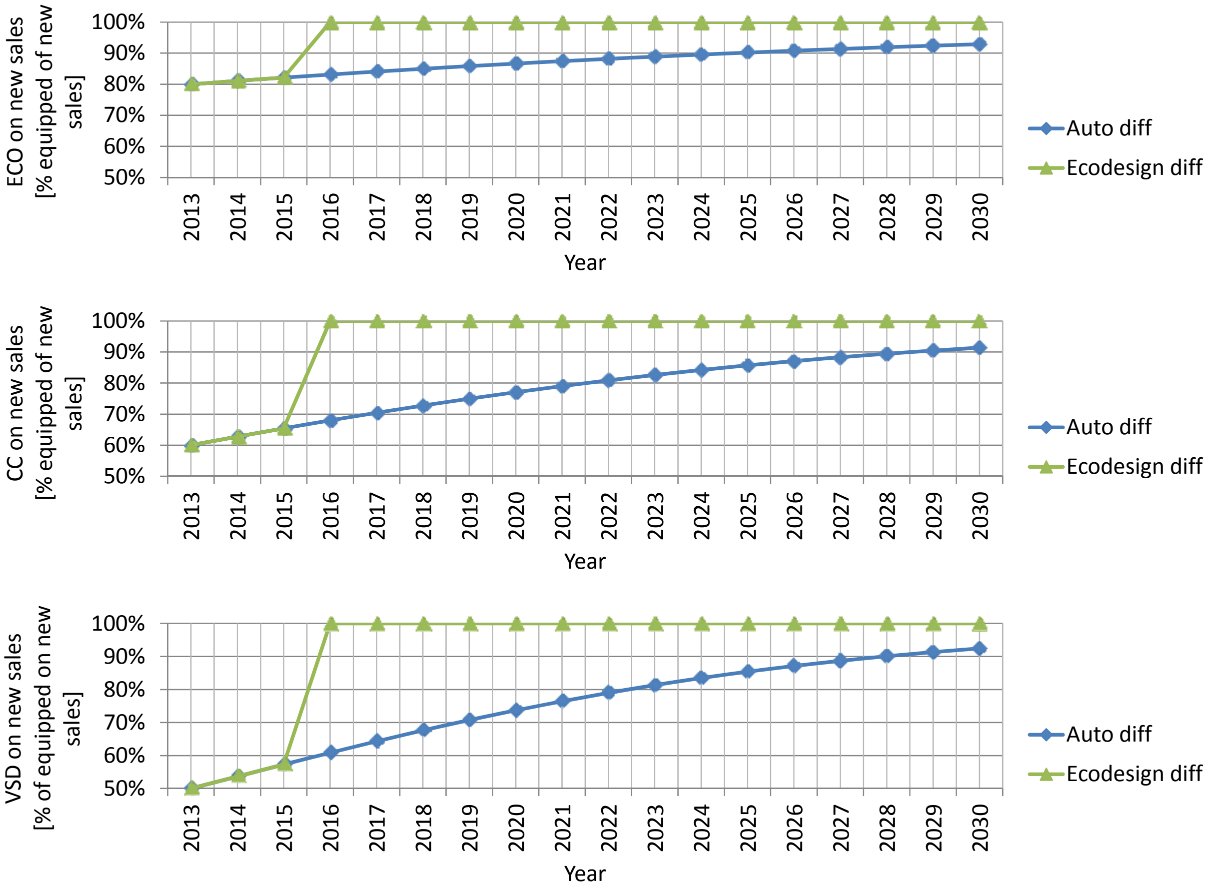

Figure 5 Assumed market shares in future for chosen design options

The results are as follows. The energy consumption (including fossil fuel at the burner and converted primary energy for the blower) rises from 908 TWh in 2013

- up to 1146 TWh in 2030 for the Auto diff, and
- up to 1138 TWh in 2030 for the Ecodesign diff (-0,7%).

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[8] The reasons for that are published in the report on Task 5 available on www.eco-steamboilers.org.

The savings per year for these scenarios are plotted in Figure 6. The sensitivity of the approach towards changes of assumed sales in 2013 and assumed energy savings per design option is tested. Thus the energy savings per design option are varied within technical meaningful thresholds (Case No. 1-9). A sensitivity analysis is also carried out in respect to the sales corresponding to the year 2013 since they constitute a major input for the building of the stock in 2013 (Case No. 10-11). Finally another variable examined is the GDP increase assumed for the future (Case No. 12-13). The variations and the resulting energy savings for the period from 2013 up to 2030 are listed in Table 4 for the differing cases.

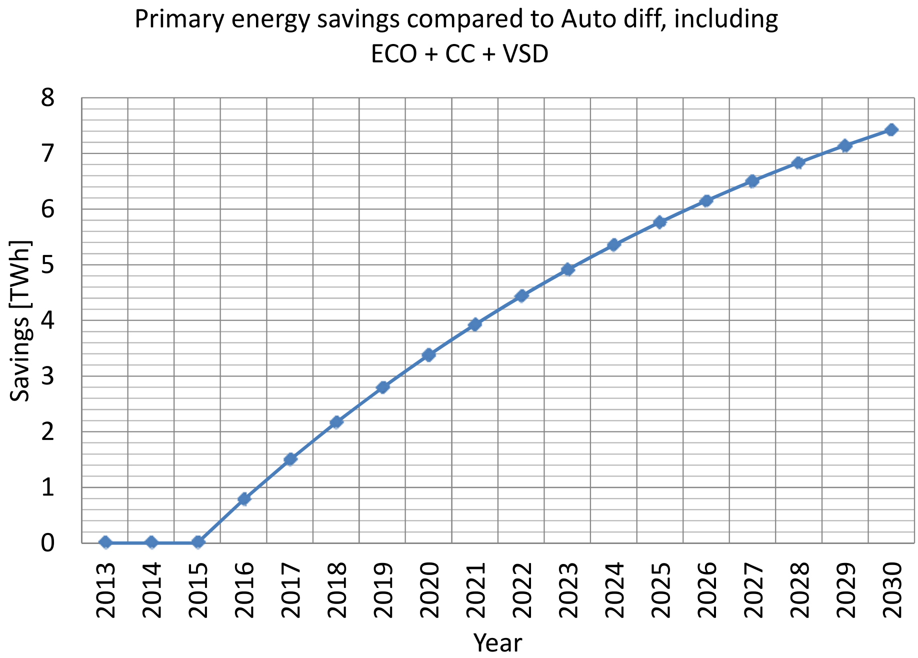

Figure 6 Predicted energy savings for the Ecodesign diff

Table 4 Sensitivity variation

Case	ECO [-]	CC [-]	APL [%]	Cumulated energy savings [TWh]*	Relative Change towards No.1	Comment
No. 1	5,50	1,75	75	71,5	0%	Reference case
No. 2	3,00	1,75	75	53,8	-25%	Low ECO savings
No. 3	7,00	1,75	75	81,3	14%	High ECO savings
No. 4	5,50	0,50	75	55,5	-22%	Low CC savings
No. 5	5,50	2,50	75	80,8	13%	High CC savings
No. 6	5,50	1,75	90	73,6	3%	Low VSD savings
No. 7	5,50	1,75	50	69,3	-3%	High VSD savings
No. 8	3,00	0,50	90	34,5	-52%	Lowest savings
No. 9	7,00	2,50	50	92,4	29%	Highest savings
No. 10	5,50	1,75	75	57,8	-19%	Sales 2013: -20%
No. 11	5,50	1,75	75	86,3	21%	Sales 2013: +20%
No.12	5,50	1,75	75	68,8	-4%	GDP growth = 1,0%
No.13	5,50	1,75	75	74,1	4%	GDP growth = 2.0%
* : for the period from 2016 to 2030.						

Discussion of results

Under the given assumptions an application of the Ecodesign directive as proposed would reduce the energy demand caused by industrial steam boilers in future. Thus, an up to 0.7% lower energy demand can be achieved compared to the Autodiff in 2030 (within the set system boundaries). The overall energy savings for the period from 2016 up to 2030 amount to 72 TWh for the reference case. Varying the energy savings per design option within technical meaningful ranges the resulting overall savings decrease by 50% or increase by 30% (cases 1 to 9). Increasing and decreasing the sales in 2013 by 20% the energy savings are also increased or decreased by 20%. This means that total energy savings are crucially influenced by assumptions on energy savings per option and stock building. Varying the assumed GDP growth for the future the differences in energy savings are not so high compared to those previously. An increase and decrease of the GDP growth in future by one third of the original value only increases or decreases the overall savings by 4%.

Conclusions and outlook

The goal of this paper was to quantify the possible impact of the Ecodesign directive on the energy savings for industrial steam boilers in Europe for up to 2030. Due to lack of data on the European stock of industrial steam boilers, the number of machines was quantified by employing a back casting approach. Furthermore, an autonomous market diffusion of efficiency options in the future for the steam boiler stock in Europe was assumed by fitting S-curves based on historical best guess market share values from industrial stakeholders. Finally, the potential energy savings for the assumed Ecodesign implementing measures were quantified. It was found that the energy savings that can be achieved by means of the Ecodesign directive are small compared to the overall consumption (based in the slow exchange within the stock). As already mentioned above, several efficiency options were omitted within this paper and the Preparatory Study as the Ecodesign framework clearly focuses on products and not systems. Although the question how to separate products from systems is not trivial in the case of industrial steam boilers, a categorization in generation, distribution, end-use and recovery system is prevalent in science and practice (U.S. Department of Energy 2012). As several studies indicate, large untapped energy savings also lie within the distribution and recovery system (Therkelsen and McKane 2013, Einstein et al. 2001). Thus a study on energy saving potentials of European steam systems is worth considering.

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