Early Stage Investment and Cost Calculation Methodologies for NO_x Reduction Measures in Large Combustion Plants

MAYER, C. [a*], MUELLER, A.-K. [a], FROEHLING, M. [a], SCHULTMANN, F. [a]

a. Karlsruhe Institute of Technology, Karlsruhe

**Corresponding author, carmen.mayer@kit.edu*

Abstract

The worldwide energy demand, especially in terms of electricity, has been rising significantly over the last few years. Even though the total share of renewable energy supply is growing, the global amount of fossil energy is still not declining. To lower at least the environmental effects of fossil fuel burning, the demand for emission reduction measures, especially in combustion plants, is becoming more prominent, in industrial as well as in emerging countries. The various implemented technologies differ in many technical and economic parameters. Consequently, their suitability depends on the specific application.

A detailed estimation of investments and operating costs is an essential basis for plant operators in the early stages of an investment decision. Furthermore, policies may massively influence a national energy market and the depending industries by defining thresholds for emission levels and other technical parameters. In industrial countries detailed simulation models are used for this purpose on a micro- and macroeconomic level. In less developed regions, however, information on costs of large combustion plants and especially of emission reduction measures is scarce. Nevertheless, policy makers have a deep interest in methods for assessing possible effects of their decisions. The Task Force on Techno-Economic Issues (TFTEI, formerly known as EGTEI – Expert Group on Techno-Economic Issues), being part of the UNECE/CLRTAP (United Nations Economic Commission for Europe/ Convention on Long-Range Transboundary Air Pollution) has therefore been working on a problem oriented cost and investment estimation tool for fossil fueled large combustion plants for the last few years. Its goal is to support policy makers to implement reasonable environmental protection standards by evaluating the microeconomic effects thereof. But TFTEI is not the only group working on that issue, other methods are in use as well, like (amongst others) the one published by the US Environmental Protection Agency (EPA) in 2003. The aim of this paper is to compare the two methods and show the specific advantages and disadvantages for cost and investment calculation of secondary NO_x reduction measures.

The two methods shall be introduced in detail, followed by a quantitative and qualitative comparison of the calculation results with regard to the usability of each method in the given context. The TFTEI method is based on specific investments of established plants that can be adapted to the needs of the considered application. The EPA method consists of a more detailed technical description of the process, which is then translated into investments and costs components via empirically determined conversion factors. Subsequently, the strengths and weaknesses of the methodologies in the context of a cost calculation tool such as the one developed by TFTEI are discussed with a special focus on the characteristics and needs of the target group. The main outcome is that a calibration of the EPA method seems reasonable, as the calculation results are a lot lower than those of the TFTEI method, but within a steady proportion. Due to a lack of data, however, a calibration is not feasible at the current state. Further surveys are recommended to improve the data base and to reduce the uncertainty of the results.

Keywords: *Techno-economic assessment, Emission Reduction, Emerging Countries, SCR, SNCR*

1 Introduction and Background

The public image of fossil energy generation has been suffering a lot over the last decades, due to the discussions on limited resources, the climate change and other negative effects caused by pollutant emission. Nevertheless, the combustion of fossil fuels is still necessary in most regions of the world, to fulfill the energy demand. The statistics of the US Energy Information Administration (US EIA, 2015) in Fig. 1 show that while the worldwide electricity consumption has been rising by 40% during the last ten years and the amount of electricity generated from fossil fuels has not only grown in an absolute manner but also in its relative share. In 2002 the worldwide share of fossil electric energy was 65%; in 2012 it reached a level of 67%.

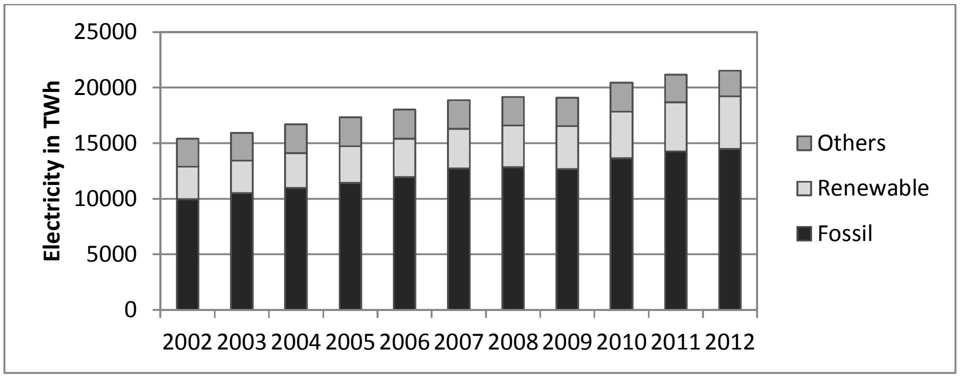


Fig. 1. Worldwide annual electricity net generation divided by fuel (2002-2012). (US EIA, 2015)

Yet to understand the situation, it is not sufficient to talk about global developments, but the local differences have to be taken into account. Fig. 2 shows the percentage shift over the last 10 years of fossil, renewable and other electricity for OECD and Non-OECD countries. The discrepancy is huge, especially regarding fossil fuels. While in the OECD countries the growth rate was still about 8%, it reached more than 95% in the rest of the world. (US EIA, 2015)

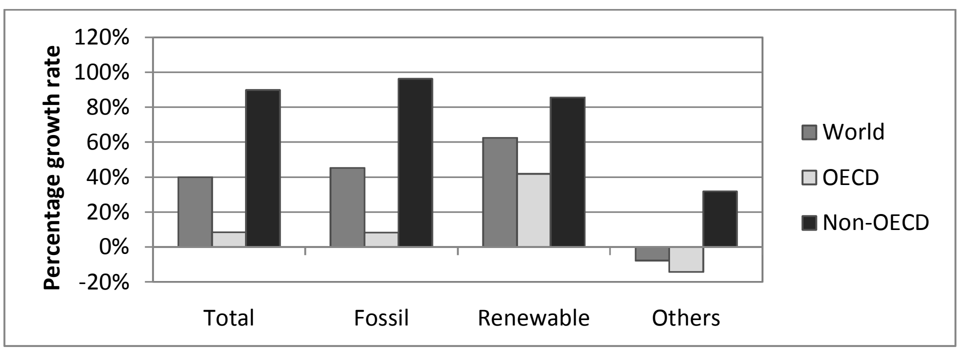


Fig. 2. Ten years percentage growth rates of the electricity net generation divided by fuel and region (2002-2012). (US EIA, 2015)

To compensate this growth rates in terms of environmental protection, it is necessary to lower the environmentally critical emissions of the generation process of electricity. A large amount of fossil fuels is transformed into electricity and heat in large combustion plants (LCP) with a thermal capacity of more than 50 MW. Therefore, emission reduction measures for these plants are an important instrument for global environmental protection programs. On the other hand, energy is a very important cost driver for many industries. Emission reduction measures in fossil fueled LCP are often end-of-pipe-technologies that have no positive cost effect like a higher efficiency would have. This facilitates the allocation of costs, but has also direct influence on the production costs of electricity, which might raise the market price (Schultmann et al., 2001). Therefore policy tends to be very conservative in terms of regulation in order to not overburden the national economy in an international context. This behaviour might be further reinforced if the assessment of effects caused by regulations is difficult or ambiguous due to a lack of investment and cost data for emission reduction measures.

To overcome this shortage of information and to support policy makers in their emission regulation efforts, EGTEI (Expert Group on Techno-Economic Issues) has been working on a cost estimation tool for emission reduction measures in LCP for several years. EGTEI is a collaboration of members of industry and administration and is working for the Working Group of Strategies and Review (WGSR) under the Convention on Long-Range Transboundary Air Pollution (CLRTAP) of the UNECE (United Nations Economic Commission for Europe). In December 2014 EGTEI has been promoted to TFTEI (Task Force on Techno-Economic Issues) by the Executive Body of the CLRTAP. This is not only an appreciation of the work that has been done (especially supporting the revision of the Gothenborg Protocol), but is also enlarging the tasks and responsibilities of the group (UNECE, 2015). TFTEI is primarily financed by the French and the Italian administration, yet other parties to the convention (e.g. Switzerland, Sweden, Finland and the European Commission) are also financing specific ad hoc activities according to the Task Force work plan priorities. To ensure the readability of this paper, the group and its work will only be named "TFTEI" below, keeping in mind, however, that a majority of the work has been done under the name of EGTEI.

Emerging countries are in general primarily dealing with questions related to the economic growth of their country. Their first aim is to maximize the economic growth and the wealth of the population. Environmental or social questions are often hardly addressed as long as people are trying to reach a certain economic status. But with a growing economy, the environmental impact of industrial processes is increasing and the community starts to pay more attention on these effects. Nevertheless, accurate cost data is hard to get for both, industrial and political decision makers. Yet with ongoing globalization most industry players are expected to be able to get data from national or international partners or benchmarking plants. Policies, however, are often facing severe difficulties in gathering data to assess the effects of their decisions. In industrial countries, detailed simulation models for a local, national or regional setting with appropriate levels of detail, according to the specific needs of the investigated issues are available. An example in this context is the RAINS – "Regional Air Pollution Information and Simulation" model (Amann, 2004) and its successor the GAINS - "Greenhouse gas – Air pollution Interactions and Synergies" model (Amann, 2012). Such Integrated Assessment Models (IAM) allow for an assessment of the economic and ecological effects of different policies on regional, national and international scales. For emerging countries, however, neither IAMs nor data for detailed techno-economic analyses of their LCP exist. Therefore they have a strong need for a problem oriented tool to assess the economic effects of their political decisions. Hence TFTEI aims at providing methods to support these assessment processes on a micro-economic level (single plant scale), by setting up an investment and cost calculation tool for emission reduction measures in LCP[1]. The tool is designed for political decision makers and is built upon an early stage investment decision knowledge base. Its aim is to deliver the best possible results without having detailed technical plant and process data. Its structure and functions will be presented below. This paper is focusing on one component of the tool, the investment and cost calculation for secondary NO_x reduction measures. A quantitative and qualitative comparison of two differing methodologies shall be presented, based on case study calculations. Further details on the tool, the scope of this paper, the methodologies and their calculation results are following in the sections below, introduced by an excerpt of important scientific literature for the subject.

2 Investment and Cost Calculation Methodologies

2.1 Literature Review

The following equation (1) has been used in several publications (Rentz, 1979; VDI, 1979; Spengler, 1998; Schultmann et al., 2001) over the last decades to calculate the costs of abatement techniques. In this approach, the total annual costs are assessed by defining the total investment first. Investment related annualized costs (depreciation, maintenance, interest, etc.) will be calculated therefrom, as the sum of all relevant subcomponents $K_{I,1}^{ERM}$, $K_{I,2}^{ERM}$,…. Summed up with the operating costs (which are as well sums of the related subcomponents), the total annual costs are defined. This general approach is

[1] The TFTEI cost calculation tool is not yet publicly available but is planned to be published after its final review within the year 2015 on the website of CITEPA (Interprofessional Technical Centre for Studies on Air Pollution, Paris): http://www.citepa.org

used in the TFTEI cost calculation tool and will be further explained in section 2.4. To avoid a dependency of any local currency all cost data in this paper shall be measured in monetary units (MU).

$$K^{ERM} = \underbrace{K_I^{ERM}}_{\text{Investment related costs}} + \underbrace{K_{ME}^{ERM} + K_{Process}^{ERM} + K_{Other}^{ERM}}_{\text{Operating costs } K_{OP}^{ERM}} \qquad (1)$$

K^{ERM} : Annual total costs for the evaluated emission reduction measure (ERM) [MU/a]
K_I^{ERM} : Costs related to investments [MU/a]
K_{OP}^{ERM} : Total operating costs [MU/a]
K_{ME}^{ERM} : Costs for inputs and outputs induced by material and/or energy flows [MU/a]
$K_{Process}^{ERM}$: Process costs for relevant unit operations [MU/a]
K_{Other}^{ERM} : Other decision relevant costs [MU/a]

Regarding the operating costs for NO_x abatement measures, the quality of the results is mainly depending on the availability of technical parameters, as the cost for electricity, reagent and catalyst (for Selective Catalytic Reduction (SCR) systems) consumption are the most important cost components. These input flows can be estimated quite precisely by using technical/chemical equations if the necessary data is available. The most complex is the calculation of the necessary volume of catalyst, because of a large number of influencing parameters that cannot be integrated into an early stage investment and cost calculation tool. However, there are approximation equations or specific catalyst volume data that can be used for study-level estimations.

Regarding the calculation of investments, various approaches exist. First of all, according to Peters et al. (2003) the total capital investment (TCI) is defined as the fixed-capital investment (FCI) that contains the plant and equipment, including the necessary investment for auxiliaries and nonmanufacturing facilities plus the working-capital (WC), what would be in this case the first fill of tanks of reagent or the initial catalyst. Consequently, the total investment includes everything that is necessary to operate the plant in the designated manner. Peters et al. grouped various approaches according to their general methodology, complexity and accuracy, as shown in Fig. 3, where A is the most accurate and G has the highest uncertainty.

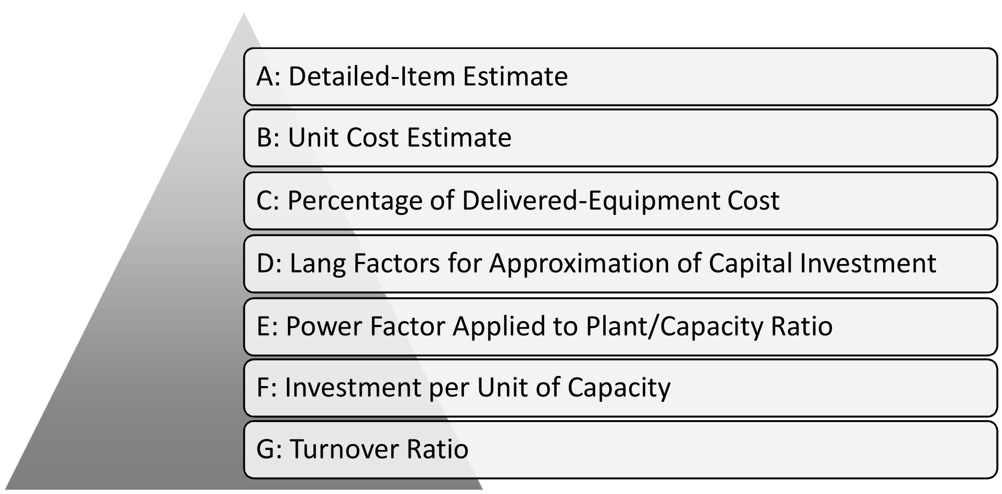


Fig. 3. Methods for estimating capital investment (cf. Peters et al., 2003)

It is beyond the scope of this paper to explain all those approaches. Nevertheless, the presented methodologies in the following chapter will be classified according to this structure, to have a general idea of their scientific background and placement.

2.2 Investment and Cost Calculation Tool

The TFTEI investment and cost calculation tool is meant to provide cost and investment data for emission reduction measures in LCP on study level with an accuracy of approximately (+/- 30%). So far only boilers are taken into account; gas turbines are regarded as a possible extension, but are not yet in scope. The tool operates in a microeconomic environment, thus only one specific plant is considered at a time.

The tool consists of calculation data for three different pollutants and three types of fuel. Fig. 4 shows a screenshot of the front page of the tool that displays all installed calculation options. Natural gas is only available for NO_x whereas for liquid fuels (oil) and solid fuels (coal, with the option of up to 20% biomass co-firing) investment and costs of emission reduction measures for NO_x, SO_2 and dust can be calculated. The regarded technologies in each configuration are listed below the push buttons.

	NO_x	SO_2	Dust
Natural Gas	Natural Gas - NOx incl. Primary Measures SCR SNCR		
Liquid Fuels	Liquid - NOx incl. Primary Measures SCR SNCR	Liquid - SO2 incl. Fuel Substitution LSFO Flue Gas Desulfurization LSD Flue Gas Desulfurization DSI Flue Gas Desulfurization with Fabric Filter	Liquid - Dust incl. ESP
Solid Fuels (coal and bio-mass)	Solid - NOx incl. Primary Measures SCR SNCR	Solid - SO2 incl. Fuel Substitution LSFO Flue Gas Desulfurization LSD Flue Gas Desulfurization DSI Flue Gas Desulfurization with Fabric Filter	Solid - Dust incl. ESP PJFF

Fig. 4. Screenshot of the 'Frontpage' of the VBA supported TFTEI cost calculation tool.

The overall calculation process is the same for all pollutants and all fuels. In a first step, the flue gas volume and the emissions of each pollutant are calculated via a number of plant and fuel parameters, depending on the selected fuel.[2] Afterwards, the preferred abatement technology for the particular fuel-pollutant combination can be selected and the necessary technical and economical parameters need to be inserted. Finally, total investment, annual costs and the amount of pollutant abated will be calculated and displayed in a summary table. References and background information are provided in reference boxes if available. The whole methodology including all equations is explained in the TFTEI cost calculation report (TFTEI, 2015) and has also been published by Müller et al. in 2013.

2.3 Scope of this Paper

The tool contains calculation data for three pollutants, NO_x, SO2 and PM. The abatement technologies for these pollutants, however, differ a lot. It is beyond the scope of this paper to investigate all of them. This work is discussing NO_x abatement technologies and their cost calculation methods with the restriction that only the secondary measures SCR (Selective Catalytic Reduction) and SNCR (Selective Non-Catalytic Reduction) have been taken into account. These are the commonly used secondary measures.

[2] The total emissions for NO_x cannot be calculated due to the complex chemical formation mechanisms. This value is therefore an input parameter that has to be filled by the user.

Furthermore the aim of this paper is not to deliver a complete overview of early stage investment and cost calculation methods, but to focus on two specific methods that had been developed and applied by the members of the TFTEI group respectively the US EPA (United States Environmental Protection Agency). They will be introduced, applied to a case study and compared in the following sections.

2.4 Characteristics of the Regarded NO_x Reduction Methods

As described above, two methodologies shall be investigated in detail in the following. The first one is the TFTEI methodology; Fig. 5 shows its general structure. After the overall plant and operating characteristics, the method splits up in an investment and an operating cost calculation path.

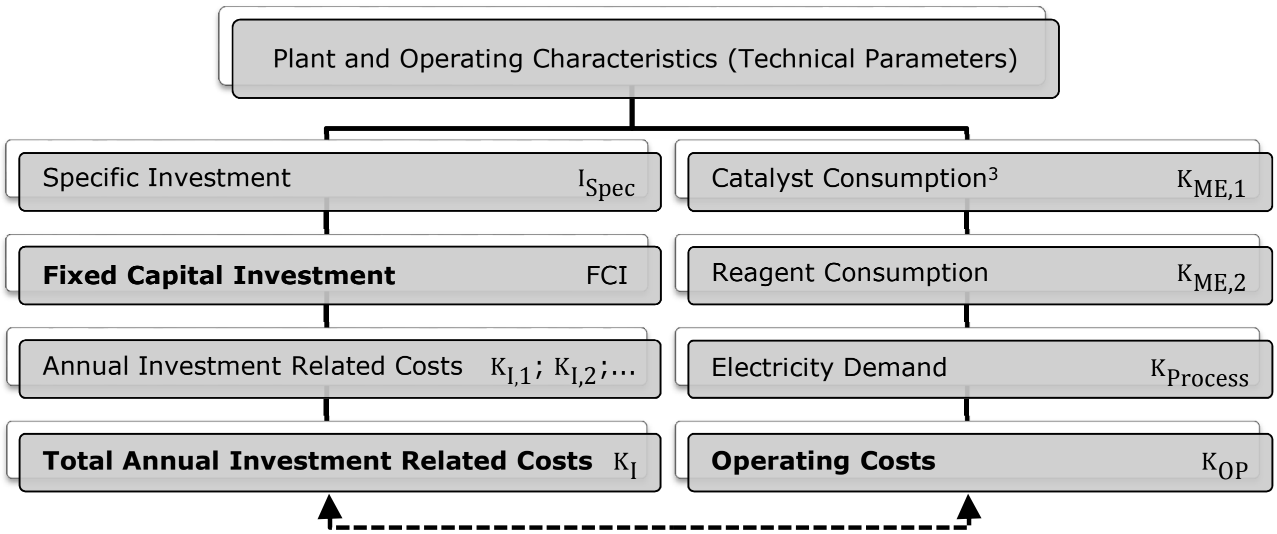


Fig. 5. Structure of TFTEI calculation method for SCR systems in LCP.

The calculation of the FCI is based on specific investments (total investment per MW_{th} installed) of existing plants. That means it can be assigned to method F (investment per unit of capacity) of Peters' scheme (Fig. 3). Values from a few exemplary plants that have been delivered by the industry members of the TFTEI group combined with literature data are available as reference or benchmarking values in the tool. If the user possesses own data of his organization or partners, it can of course be used as well. Economies of scale are not automatically taken into account, as the size of the reference plant might not be known and the power factor can vary (Peters et al., 2003). The total annual investment related costs are then calculated using typical economic input parameters like the depreciation time or the interest rate. The calculation of the operating costs includes the catalyst (in case of SCR), the electricity consumption based on the pressure drop caused by the SCR/SNCR and the consumption of the system itself. Furthermore the reagent consumption is taken into account for both, SCR and SNCR. Operation and maintenance costs are included into the tool as a percentage of the FCI and can therefore be regarded as part of the operating costs (Peters et al., 2003) or of the annual investment related costs (Schultmann et al., 2001), depending on the definition that shall be applied. In the TFTEI tool they are assigned to be operating costs because the total annual investment related costs are not displayed separately. This, however, is a question of allocation of costs and has no quantitative influence on the final results.

The structure of the EPA method (US EPA, 2002), is not split up in two separate paths, but combines the calculation of the FCI and the operating costs. It can be defined as a combination of method B (unit cost estimate) and D (Lang factors for approximation of capital investment) of Peters' methods. In several steps the technical characteristics of the regarded plant are examined. Starting with the plant and operating characteristics (e.g. thermal capacity, hours of operation, NO_x emissions without abatement and the emission limit, etc.), the total flue gas volume is calculated. In an equation with empirically determined correction factors for the removal efficiency, the inlet NO_x content, the accepted

[3] The catalyst consumption is only relevant for SCR, not for SNCR systems.

ammonia slip, the sulfur content of the coal and the inlet temperature, the catalyst volume is estimated. The SCR reactor dimensions are calculated afterwards, taking into account the flue gas and the catalyst volume together with some other influencing parameters. The reagent consumption is mainly depending on the stoichiometric ratio and the chemical reaction equation. Furthermore, the tank size is taken into account, which is relevant for the FCI, depending of the on-site storage capacity for the reagent. Finally the power consumption is calculated from another empirical equation accounting for the pressure drop and the electricity consumption of the SCR/SNCR itself. The catalyst replacement cost is directly linked to the lifetime of the catalyst and the catalyst volume via the catalyst cost per cubic meter. The FCI is a function of the flue gas volume, the reactor dimension, the tank size and again various adjustment factors, for instance for retrofits versus new plants, the existence of an SCR bypass, the reagent flow rate, and factors for contingencies, engineering, etc.. Furthermore the working capital is added to define the total capital investment. The annual costs are calculated similarly to the TFTEI method from the already mentioned influencing parameters (catalyst, reagent and electricity demand). (US EPA, 2002). This approach is a lot more detailed and might thus be more accurate. On the other hand, the origin of the factors and the cost data is very nontransparent and might be outdated, as the methodology has been published in 2002. An actualization seems to be inevitable, but without having a survey with detailed plant data, it is hardly possible. Further discussions on that will follow in chapters 3 and 4.

3 Application and Results

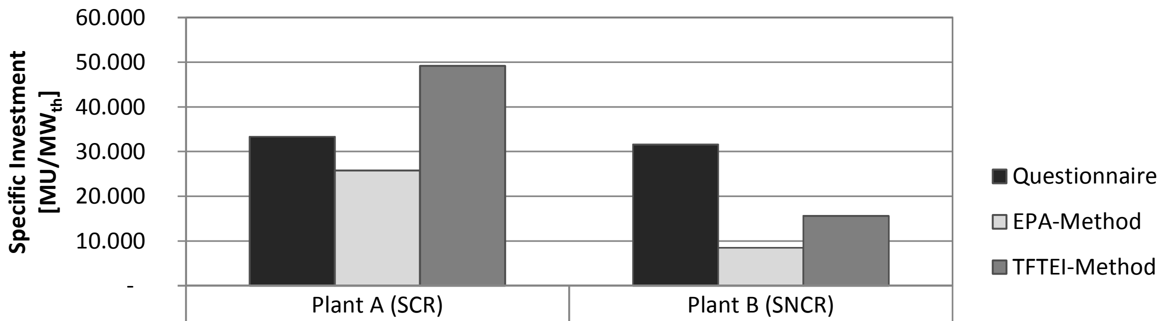
3.1 Case Studies

To compare the results of the methods, two case studies with exemplary data sets are carried out. Such data is hardly available since plant operators do not want to publish detailed technical and economical data of their sites. In 2012, however, the former EGTEI group carried out a survey on the techno-economic evaluation of emission reduction measures in LCP. A substantial questionnaire was sent to plant operators, asking for specific plant data concerning the combustion process itself and emission reduction measures for NO_x, SO_2 and PM. The response was very low, two examples thereof are, however, forming the database for the following case studies. Unfortunately these data sets are far from being complete for both EPA and TFTEI. Consequently assumptions have been made for all missing parameters, following the reference values that have been investigated for most input parameters of the TFTEI tool. Some of them have a massive influence on the results, for example the total investment path of the TFTEI method is mainly based on specific investments. The range for this value is very broad, depending on national, geographical, technical and many other influences. For the exemplary datasets, an average value has been used that might differ from what specialists or plant operators would have estimated for the plant, therefore the datasets have to be seen as fictional plants. The aim of this paper is thus not to deliver absolute results for the total investments and operating costs of the regarded measures but to compare the results of the two methodologies. This is also the reason why, as described above, monetary units (MU) are used instead of existing currencies.

The two regarded plants below have the following characteristics: Plant A has a capacity of 1500 MW_{th} that uses an SCR system for flue gas treatment. Plant B has 620 MW_{th} installed power and is equipped with an SNCR system. Both plants are coal fired (without biomass co-firing) and do not dissipate heat for other applications.

3.2 Quantitative Comparison of the Investment and Cost Calculation Methods

Fig. 6 shows the results of the case studies. The specific investments given in the questionnaires are compared with the results of the EPA and TFTEI investment calculation. Keeping in mind that the data sets can be described as fictional data due to the number and influence of the assumptions, the most interesting part is the comparison between EPA and TFTEI. In both cases, the EPA value is a lot lower than the TFTEI one; the difference is 48% for plant A and 46% for plant B. This is caused by the aberration between the average specific investment value that has been examined by TFTEI and the cost factors implemented in the EPA method. One reason therefore might be a geographical influence, as the EPA data has been collected in the US, whereas TFTEI relies on data from European plants. Other influences are also possible and should be investigated in further detail in the future, as they are hard to trace due to the lack of realistic data. Even though these case studies are far from being statistically significant, however, the proportion between the EPA and TFTEI results is quite steady, which implies the possibility of a calibration of the EPA method, if more recent and detailed cost and investment data can be gathered. Due to the strong influence of the specific investment, a calibration for the TFTEI method is not feasible; the quality of the results is directly depending on the accuracy of the assumption for that value.



	Plant A (SCR)	Plant B (SNCR)
Questionnaire	33.333	31.584
EPA-Method	25.791	8.473
TFTEI-Method	49.210	15.647

Fig. 6. Quantitative comparison of questionnaire data, EPA- and TFTEI-method calculation results for specific investments of secondary NO_x emission reduction measures.

Regarding the total annual operating costs, the results of the EPA method are 31% lower for the SCR plant and 33% lower for the SNCR plant. Fig. 7 shows the distribution of the cost components for the SCR plant. The 'operation and maintenance' block has been taken into account for the calculation, but is not part of the diagram as it is a share of the TFI in both methods and therefore leads to inter-dependencies between the investment and the operating cost calculation. The deviations between the methods are based on the technical equations. Slight aberrations in the calculation of the total flue gas volume and the reagent consumption lead to a significant cost difference due to the large total amount of reagent consumed. Regarding the catalyst replacement cost, TFTEI is using the parameter 'specific catalyst volume' that has the same influence as the specific investments has for the FCI calculation. The electricity consumption is calculated based on technical input parameters in TFTEI and based on an empirically determined average equation in EPA, what leads to the shown aberration.

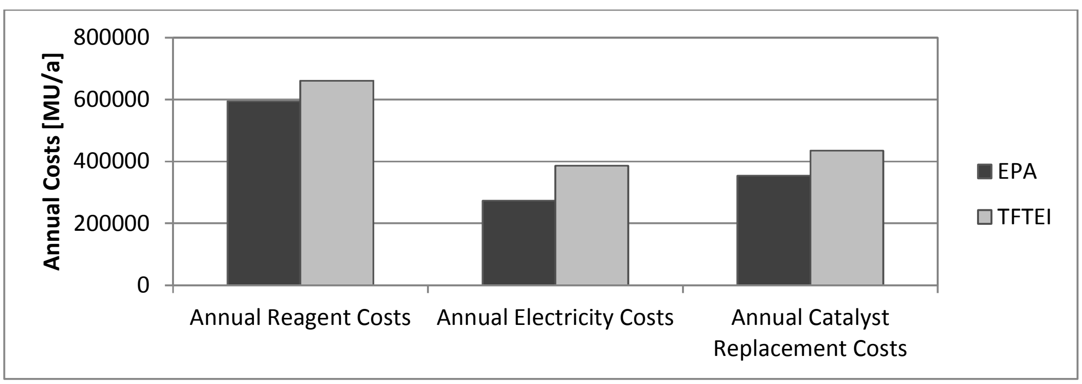


Fig. 7. Comparison of the annual operating cost components for plant A (equipped with SCR) for the EPA and TFTEI method.

3.3 Qualitative Comparison of the Investment and Cost Calculation Methods

Apart from the quantitative results, the case studies show many more interesting facts about the usability of the two methods. Some of them have been mentioned before; all of them are summed up in Fig. 8 to give an overview. The most important conclusion of this table is, that the EPA method is technically more detailed, what facilitates the estimation of missing values (as they are more specifically defined), but leads to the fact, that a lot more parameters are necessary and the calculation is less transparent. The TFTEI method is using less input parameters and is therefore clearly arranged and more adaptable if detailed knowledge and background information is available, but on the other hand, the influence of individual parameters is a lot higher so that estimation uncertainties have a stronger impact on the final results.

Fig. 8. Advantages and disadvantages of the EPA and TFTEI calculation methods.

	EPA	TFTEI
Advantages	Lower dependence on single parameters (due to factor based calculation)	Higher transparency (no empirically determined factors), less complex calculations
	No experience with existing plants necessary (no assumption of specific investments)	Literature based reference data (more perspicuous and easier to update)
	Higher possible accuracy due to more precise technical process reproduction in the economical equations	Higher flexibility through specific investment adaptation
	Detailed documentation and calculation example (US EPA, 2002)	Less input parameters necessary
Disadvantages	Many technical parameters necessary to execute the calculations	Strong dependence on specific investments (if no good assumption can be made for this value, the results are very uncertain)
	No individual influence parameter (e.g. specific investment) that takes the complexity/ circumstances of the system into account	Neglect of technical configuration in terms of water consumption, tank size, design and size of the reactor (for SCR), etc.
	Few information on origin of cost factors, therefore hard to update	Less detailed consideration of economic factors (contingencies, engineering, etc.)

A recommendation based on this comparison would be, not to differ between "good and bad" but to implement both methods in the tool and to highlight the individual advantages and disadvantages so that the user can select the suitable methodology for his needs. According to the circumstances and the available database for a specific application, the one or the other method might be more appropriate. Both methods need a technical understanding of the plant to identify and understand the necessary input parameters. The future goal should be to provide as much background information as possible, to facilitate the evaluation of specific input parameters and to improve the quality of assumptions if they cannot be avoided.

4 Conclusion and Outlook

Resuming the results of this paper, there is no obvious suggestion to be made for one method to be preferred. Concerning the specific needs of the addressees, the best solution might be, to offer both alternatives in the TFTEI tool. This implies that both methods need to be implemented and explained in the documentation to enable the user to select the appropriate one for his application. In a longer-term perspective, the implementation of an automated methodology selection algorithm based on the number, type and quality of the available input parameters seems to be an option to further facilitate the usage of the tool. For more industry related users, who have detailed plant data, the EPA method might be the better one. On the other hand, with TFTEI it is possible to get a result even if only very few technical parameters are available. Nevertheless the accuracy can be questioned due to the strong dependency of the specific investment input parameter.

To improve the quality of the results, a calibration of the EPA method is recommended. The publication of the method was more than 12 years ago and some of the factors seem to be outdated. To do that, a specific survey is necessary which allows the comparison of real data from existing plants with the EPA and the TFTEI results. Furthermore some of the technical equations in the EPA method can be questioned. The estimation of the number of catalyst layers delivered a very high result in the SCR example. As a lot of research has been done on the ideal catalyst configuration over the last few years, an update – or at least the possibility to input the number of layers directly – might be necessary. This shall just be an example for a possible update on the technical side, which is not directly cost-related.

Furthermore, cost indexes (e.g. the CEPCI index) have not been taken into account in the examples, as the cost year was not always known. This can of course be implemented into the tool, nevertheless it will not have an effect on the relative distribution of the results, as it will be applied on the investment calculation of both methods. Moreover the case studies made obvious, that the EPA method considers cost drivers, that have an insignificant influence on the final results (below 1%), especially compared to the study-level accuracy (+/- 30%) of the whole methodology. These effects have not been taken into account for the calculation of the case studies and are not recommended for consideration in future applications.

From a wider perspective, future improvements of the tool could be the investigation of further methodological approaches for investment calculation according to the scheme of Peters et al. (chapter 2.1) or the consideration of integrated concepts like the net present value method or the real option analysis. It should be kept in mind, however, that for the purpose of this tool, the usability and transperency of the calculations should stay in the focus and the availability of data will be limited for most users, so that very detailed models will not automatically improve the quality of the results and the actual level of support for the addressees.

5 References

Amann, M., Cofala, J., Heyes, C., Klimont, Z., Mechler, R., Posch, M., Schöpp, W., 2004. The RAINS model. Documentation of the model approach prepared for the RAINS peer review, Interim Report.

Amann, M., 2012. The GAINS Integrated Assessment Model. European Consortium for Modelling of Air Pollution and Climate Strategies - EC4MACS. IIASA.

Müller, A.-K., Schulte Beerbühl, S., Fröhling, M., Schultmann, F., 2013. Methodology for Economic Assessment of Best Available Air Pollutant Abatement Techniques for Thermal Power Plants. Conference Proceedings of "Pollution and Environment - Treatment of Air" (PETrA), Prague.

NESCAUM, 2000. Status Report on NOx Controls for Gas Turbines, Cement Kilns, Industrial Boilers, Internal Combustion Engines. Northeast States for Coordinated Air Use Management. www.nescaum.org/documents/nox-2000.pdf/, last accessed February 2015.

Peters, M., Timmerhaus, K., West, R., 2003. Plant Design and Economics for Chemical Engineers. 5. McGraw-Hill Education, New York.

Rentz, O., 1979. Techno-Economy of Industrial Emission Reducion Measures. Techno-Ökonomie betrieblicher Emissionsminderungsmassnahmen (in German), Erich Schmidt Verlag, Berlin.

Schultmann, F., Jochum, R., Rentz, O., 2001. A Methodological Approach for the Economic Assessment of Best Available Techniques. The International Journal of Life Cycle Assessment. Volume 6, Issue 1, 19-27.

Spengler, T., 1998. Industrial materials flow management - economic planning and control of materials and energy flows in manufacturing plants. Industrielles Stoffstrommanagement - Betriebswirtschaftliche Planung und Steuerung von Stoff- und Energieströmen in Produktionsunternehmen (in German). Erich Schmidt Verlag, Berlin.

TFTEI, 2015. Estimation of Costs of Reduction Techniques for LCP – Methodology. TFTEI technical secretariat.

UNECE, 2015. Report of the Executive Body on its thirty-third session - Decisions adopted at the thirty-third session, United Nations Economic Commission for Europe. http://www.unece.org/fileadmin/DAM/env/documents/2014/AIR/EB/ece.eb.air.127.add.1.AV.pdf, last accessed February 2015.

US EIA, 2015. International Energy Statistics, United States Energy Information Administration. http://www.eia.gov/cfapps/ipdbproject/iedindex3.cfm?tid=2&pid=2&aid=12&cid=regions&syid=2002&eyid=2012&unit=BKWH, last accessed February 2015.

US EPA, 2002. Air Pollution Control Cost Manual. 6. EPA/452/B-02-001, United States Environmental Protection Agency.

VDI Richtline 3800, 1979. Determination of the cost of emission control activities. Kostenermittlung für Anlagen und Maßnahmen zur Emissionsminderung (in German). VDI-Handbuch Reinhaltung der Luft 6, Düsseldorf.