CZECH TECHNICAL UNIVERSITY IN PRAGUE
FACULTY OF ELECTRICAL ENGINEERING
DEPARTMENT OF ECONOMICS, MANAGEMENT AND HUMANITIES

EVALUATION OF ENERGY EFFICIENCY POLICY INSTRUMENTS

Habilitation Thesis

Michaela Valentová

Prague, August, 2018

COPYRIGHT

This work is a compilation of papers published throughout the course of my research. The articles included in this habilitation thesis are protected by the copyright of Wiley Periodicals, Taylor and Francis, and Elsevier. They are presented and reprinted in accordance with the copyright agreements with the respective publishers. Further copying or reprinting can be done exclusively with the permission of the respective publishers.

ACKNOWLEDGEMENTS

I would like to thank my colleagues and co-writers, namely Jaroslav Knápek, Jiří Karásek, Tomáš Králík, and Paolo Bertoldi for the great work and cooperation on the research. It is a pleasure to be part of the team and have the opportunity to work with such bright and open minds.

I would like to extend my thanks especially to Prof. Knápek not only for bringing in his expertise, but for being highly supportive and encouraging throughout both the habilitation process, and the academic life as such.

Abstract

The habilitation thesis presents the advances in the research of the energy efficiency and renewable energy sources (RES) policy evaluation. It focuses on selected areas in this field. Specifically, the habilitation thesis addresses the following issues:

- The evaluation of the cost-effectiveness of energy efficiency and renewable energy policies with a special focus on the cost-effectiveness of intentionally grown biomass for energy purposes. A systemic approach to the evaluation of the cost-effectiveness of energy biomass is presented, providing better insight and background information for proper decision making. We show that in the current economic and policy framework of the Czech Republic (with a possible extension of the results to Central Europe), the energy biomass is not competitive.
- The inclusion of transaction costs in energy efficiency and renewable energy policies. We examine the role of various factors on the structure and size of the transaction costs on a case example of two major energy efficiency and RES subsidy programmes, concluding that the potential for optimisation lies in streamlining the internal processes and a clear legal environment. For public bodies, room for improvement likes especially in the tendering for external services.
- The importance of ex-post evaluation of the real outcomes of specific policy instruments. On a case example of one of the biggest subsidy schemes in Europe, we provide evidence that there is a significant difference between the ex-ante (expected) outcomes and the ex-post (real) outcomes of the programme. We also give insight into the main reasons why this is happening.

TABLE OF CONTENTS

1. INTRODUCTION

In 2010 the European Commission launched the Europe 2020 initiative, which sets ambitious targets to be reachedand by 2020. Among others, a 20 % increase in energy efficiency should be attained (European Commission 2010). Similarly, The EU set a binding target of 20 % final energy consumption from renewable sources by 2020 (European Parliament and Council 2009). Recently, within the negotiations over the so-called Winter Package, the Commission, the Parliament and the Council negotiated a binding renewable energy target for the EU for 2030 of 32%.

The Energy Efficiency Directive (European Parliament and Council 2012), adopted in 2012, sets out a further set of binding measures that should help the EU Members States reach the energy efficiency target (with spill overs to renewable energy targets). It requires that energy distributors or retail energy sales companies (or the Member States, if they opt for so-called alternative policy measures) achieve 1.5% energy savings per year through the implementation of energy efficiency measures. Furthermore, 3% of the total floor area of heated and/or cooled buildings owned and occupied by the EU Member State central governments has to be renovated each year.

The buildings consume about 40 % of energy in developed countries and about 75 % of buildings in the European Union (EU) Member States (MS) are considered as insufficient regarding energy efficiency (European Commission 2016). Therefore, there is still a significant potential for improvement of the buildings stock and a decrease in energy consumption.

To this end, many supporting schemes (be it EU operational programmes or programmes at the national level) have been set up. The European Union supports its Member States in achieving the goals by providing a substantial level of funding through its Cohesion Policy programmes. In the programming period 2007 – 2013 a total of EUR 6.1 billion was allocated to the priority theme "Energy efficiency, co-generation and energy management", representing 2% of the total allocation (Ramboll and Institute for European Environmental Policy 2016). Furthermore, the theme "Enterprise" (under which energy efficiency and RES improvements have also been co-funded) was supported with EUR 51.9 billion, i.e. about 20 % of total ERDF and Cohesion Fund support in the EU during the 2007 – 2013 period (Applica and Ismeri Europa 2016).

However, the pace of improvement is still not high enough, and neither is the level of monitoring and evaluation. Given the ambitiousness of the goals and the significant levels of expenditures allocated to reach them, it is crucial that careful evaluation (ex-ante and ex-post) is carried out to ensure that the public money is spent effectively.

The thesis provides an insight into the selection of challenges remaining in the field of energy efficiency and RES policy evaluation. It focuses on the three main aspects that have been underdeveloped both in the academic debate and in the policy design. These are the correct calculation of the cost-effectiveness of the policy instruments, the transaction costs of energy efficiency and RES policy measures, and the ex-post evaluation of real outcomes of the policies and programmes. The thesis is based on the research and results published by the submitter.

The second chapter provides background information on the main areas of research exploited, i.e. the proper economic evaluation of energy efficiency and RES instruments, the need to include transaction costs in the evaluation processes (and the main factors influencing the transaction costs), and the inadequacies of ex-post monitoring of the energy policy outcomes. The main aims of the thesis reflect the identified research gaps. The main body of the thesis is then composed of the main results of the research articles which addressed the identified research gaps. Conclusions convey further areas of research of the submitter.

2. ENERGY EFFICIENCY AND RES POLICY EVALUATION – BACKGROUND

Policy targets should be SMART, i.e. specific, measurable, appropriate, realistic, and timed (Rietbergen and Blok 2010). Specificity and measurability are the key components relevant to the evaluation of the policy. As Harmsen (2014) puts it, "[w]ithout knowing what to achieve, and without having data about the progress towards target achievement, evaluation becomes an impossible mission".

In the Czech Republic, the energy efficiency (and RES) programmes tend to be evaluated only from the viewpoint of allocated public finances (and whether they have been spent out). Partially, the attained results are reported too – mostly the energy savings achieved (or planned to be achieved) due to the reporting requirements of the Energy Efficiency Directive (European Parliament and Council 2012), and the Renewable energy Directive (European Parliament and Council 2009). However, several areas keep being omitted in the evaluation processes (the same, to a large extent, applies to the situation in other countries in the EU).

Firstly, economic evaluation of the policy instruments remains insufficiently addressed. Often, in the policy design (and in the academic debate, too), the concepts of opportunity costs, time dimension of the effects, additionality of the measures, and other, are not correctly addressed. Furthermore, as, e.g. Oikonomou highlights the cost-effectiveness of a policy instrument tends to change (decrease) over time, and creates the need for regular policy instrument adaption (Labanca and Bertoldi 2017).

Secondly, one of the omitted parts of (cost-effectiveness) evaluation is the administrative burden (or transaction costs) of the policy instruments, both on the side of the applicants (or target audience), and on the side of the administrators of the policy instruments. Unsystematic evaluation of the processes and related costs of the programmes can then lead to suboptimal decision making. The public finances can be distributed ineffectively, and at the same time, the energy efficiency targets are not being attained.

Thirdly, ex-ante evaluation of the policy instruments largely prevails over ex-post evaluation. For instance, Hildén et al. (2014) note that only less than 10% of the entries in the 2011 reporting cycle of the climate policies in the EU Member States included quantitative data based on ex-post evaluations. It means that the real outcomes of the programmes are rarely known. For various reasons (discussed further) lack of ex-post evaluation may lead to misinterpretation of the results of the programme, differences in the attained targets, and ultimately in misinterpretation of its overall effectiveness.

The three aspects are discussed in detail in the following subchapters.

2.1. Cost-Effectiveness Evaluation

An important goal in the policy analysis is to provide information on how the results of the policy relate to the costs expended on the programme. The correct evaluation of the costs and benefits remains one of the burning challenges both in the academic debate and for the policymakers. Correct calculation of cost-effectiveness allows for comparison between the different policy designs and helps to set the optimal policy mix (Harmsen 2014). In general, a benefit-cost ratio above 1 means the program has positive net benefits, which is desirable (Environmental Protection Agency 2008). Often, the cost-effectiveness is defined as reaching the target (the benefits) with minimum costs (del Río and Cerdá 2014).

There are three main approaches to evaluate the cost-effectiveness (Yushchenko and Patel 2017). Firstly, it is the private investor's (or technical) point of view, comparing the costs of the energy efficiency measure to the reduction of energy consumption thanks to the measure (employed by, e.g. (McNeil and Bojda 2012; Ecofys 2017)). The similar can be calculated for renewable energy sources (e.g. by (Kasmioui and Ceulemans 2013)). Ever more often now, the multiple benefits of energy efficiency measures (such as health improvement, environmental benefits, and other) tend to be addressed, and the idea is that they, too, should be part of the cost-benefit analysis (Campbell 2014).

The second approach takes into account the administrators point of view (also discussed in the previous subchapter). In such case, the programme costs (or the costs of the incentives) are compared to the results of the programme (McCann 2013; De la Rue du Can et al. 2014). Yushchenko and Patel (2017) argue that, while better for policy evaluation, this approach is incomplete, too, as it does not take into account the impact of the policy instrument(s) on other stakeholders, such as utilities and ratepayers. Therefore, they advocate a third approach, the multiple-stakeholder perspective (Environmental Protection Agency 2008), in which they calculate the cost-benefit analysis for various actors, including administrators, participants of the programme, ratepayers, and utilities.

It must be noted that the actual estimate of the costs and benefits is not straightforward. Additionally, the comparison between countries and between policy instruments may be tricky, due to differences in methodology, and interactions between the measures (Labanca and Bertoldi 2017).

Following the above debate, in our research, we have specifically focused on the challenges of economic evaluation of RES policies. We have selected biomass intentionally grown energy purposes to show further challenges to RES cost-effectiveness calculation. The reason is that energy biomass plays an increasingly important role in both the EU and the Czech Republic energy strategies and is expected to play the decisive role in fulfilling EU 2030 goals in renewable energy sources (RES). Since sources of residual and waste biomass are quickly depleted, further increase in the exploitation of biomass for energy purposes (as a decisive RES contributor in the Czech Republic) can be guaranteed only by intentionally grown biomass.

In the current academic debate on the economics of energy biomass, three main approaches can be recognised. First, various aspects of the energy biomass supply chain are thoroughly described, including economic, social, and environmental aspects of growing of biomass for energy purposes (Cambero and Sowlati 2014). Economic models determining future biomass prices reflect in detail typical processes of a given type of biomass related to growing, harvesting, storage, processing if needed, and other parts of the logistic chain from the biomass producer to the final consumer (Kasmioui and Ceulemans 2013; Fazio, Barbanti, and Venturi 2009; van der Hilst et al. 2008).

Second, the studies compare the economic viability (competitiveness) of biomass for energy purposes with conventional crops, such as wheat. The idea lying behind is that the arable land is a scarce (limited) resource, and farmers decide on which purpose it will be used for, taking into account economic criteria (profitability) (Sgroi et al. 2015; Gasol et al. 2010; Krasuska and Rosenqvist 2012; Styles, Thorne, and Jones 2008). In such studies, the main focus remains on the calculation of energy biomass production costs (Hauk, Knoke, and Wittkopf 2014).

Third, authors analyse the market demand, where biomass (or other RES) substitutes fossil fuels, such as coal, exploited in power generation and heat production, and in household heating systems (Nasiri et al. 2016; Cansino et al. 2011). Furthermore, the studies focus on the assessment and analysis of RES support schemes (Gawel et al. 2017; Huber et al. 2007; Klessmann, Nabe, and Burges 2008).

Only by combining the three above-mentioned approaches in one general model, one is able to make informed decisions on the growth in production of biomass for energy purposes, estimate the ‘real’ biomass contribution to the primary energy sources (PES) balance, based on its market competitiveness, and formulate the cost-effective policy instruments for that matter.

In conclusion, we show that a systemic approach to energy efficiency and RES policy evaluation is essential to properly assess the economic implications of the various policy instruments. The key stakeholders have to be identified together with the costs and benefits on which they base their decisions.

2.2. Transaction Costs

Closely related to the previous subchapter, the negative impact of the transaction on the implementation of energy efficiency and RES policy measures has been acknowledged and supported by a number of studies (Ostertag 1999; Reddy 1991; Sanstad and Howarth 1994). Transaction costs can hinder implementation of energy efficiency and RES policy measures or even prevent them from being implemented at all (L. T. Mundaca et al. 2013). However, transaction costs have not been systematically taken into account when designing energy efficiency and RES policies and have not been systematically evaluated ex-post, either (McCann et al. 2005). Therefore, the information on the overall effectiveness of (public) programmes tends to be incomplete.

The transaction costs theory is embedded in the New Institutional Economics theory, which stipulates that all actors in the economy make their decisions with bounded rationality (Musole 2009). The concept of transaction costs helps to explain how institutions affect economic efficiency (Schofield, Caballero, and Kselman 2013). All transactions (and contracts) induce transaction costs. Not including transaction costs in the decision-making leads to suboptimal decisions from the system point of view as a substantial part of the reality is neglected.

There is not an academic consensus on a common definition of transaction costs (McCann et al. 2005; Musole 2009; Ostertag 2003). North (1990) categorises transaction costs to market costs (such as legal fees) and costs of time that the actors spend to gain the necessary information. Importantly, the transaction costs always consist of a variable part (dependent on the size of the project) and the fixed part (independent of the size of the project) (Musole 2009). The categorisation then tends to be case specific. Michaelowa and Jotzo (2005), for instance, identified the costs of monitoring as fixed costs and costs of negotiation as variable costs. The typical phases during which the transaction costs of energy efficiency programmes arise would be planning, implementation, monitoring, and evaluation (L. T. Mundaca et al. 2013; Rao 2003).

The methods to measure transaction costs differ in different studies and are tailored to the specificities of the studied policies and measures (L. T. Mundaca et al. 2013; Musole 2009). As Cheung (1998) puts it, "[t]he [transaction costs] paradigm (...) is simple but difficult. The difficulty lies in the thorough empirical investigation required (...)".

The key drivers that influence the size and structure of transaction costs have been summarised by, e.g. (Coggan et al. 2013; L. T. Mundaca et al. 2013; Musole 2009). Firstly, the actors in the transactions (projects) are one of the main drivers. Ahonen and Hämekoski (2005) found dependence between the transaction costs and the "competence and capacity of project developer". Coggan et al. (2013) identify the characteristics of the transactors (their experience, capacity to assess information, etc.) as one of the core factors influencing the structure and level of transaction costs. Relatedly, the institutional environment and internal rules, in which the actors carry out the transactions, adds to the defining factors of transaction costs (McCann 2013; Shahab, Clinch, and O'Neill 2018).

Secondly, it seems that transaction costs can to some extent be lowered thanks to the effect of a "learning curve" (Lee and Han 2016; Michaelowa and Jotzo 2005). However, the extent to which this is possible may depend on the character of transaction costs (Kiss 2016).

On the one hand, Musole (2009), citing (Furubotn and Richter 2000) concludes that given the complexity of the whole (macroeconomic) system, "even if cost-minimising (...) institutions could have been established in the past, there is little chance that they could still be the optimal solutions of the present." On the other hand, the empirical evidence in energy efficiency programmes suggests that there is a positive effect of a "learning curve", i.e. that transaction costs can become lower thanks to the gained experience. For instance, Falconer et al. (2001) emphasised that the transaction costs (in agro-environmental mechanisms) tend to decrease thanks to administrative learning and fine-tuning of the processes. Similarly, Lee and Han (2016) found that "emissions trading scheme works inefficiently in its early stages, however, it could gradually be improved due to the learning curve effect". Michaelowa and Jotzo (2005) in their case study on programmes under the clean development mechanism (CDM) conclude that transaction costs decline over time, supporting the hypothesis on the effect of learning. Kiss (2016) emphasizes that the extent to which this is possible may depend on the character of the transaction (i.e. the source of transaction costs). McCann et al. (2005) add that the transaction costs decrease over time due to the existence of fixed (sunk) costs, which incur at the beginning of the programme.

Thirdly, various studies (e.g. Bakam, Balana, and Matthews 2012; Jaraité, Convery, and Di Maria 2010; Michaelowa and Jotzo 2005; Sathaye and Murtishaw 2004) have concluded that transaction costs depend indirectly on the size of the project (or the environmental effect of the policy measure), i.e. the bigger the project (or the higher the environmental effects), the lower the burden of transaction costs. Michaelowa et al. (2003) believe one of the main reasons is the different share of the variable component and fixed component in the total transaction costs. Falconer et al. (2001) note that this offers a room for economies of scale.

Even though the debate on transaction costs has developed vastly from the beginnings, the empirical evidence of transaction costs particularly in energy efficiency and RES policies and programmes remains inadequate. Specifically, the number of quantitative estimates is limited (McCann et al. 2005; L. T. Mundaca et al. 2013). The available empirical studies all conclude that transaction costs are of non-negligible levels, ranging roughly from 8 % to 40 % relative to the compared unit of measurement. For instance, Jaraité et al. (2010) estimated the transaction costs of three programmes aimed at efficient transport. They found that the transaction costs ranged from 3 % (of total costs of a fuel efficiency programme) to over 18 % (of compliance costs of the Fuel Label Program). Björkqvist and Wene (1993) analysed the transaction costs of energy efficiency measures in households. They estimated the level of transaction costs at 28 % of the level of energy efficiency investment (using gross labour to express the transaction costs). Mundaca (2007) analysed the white certificates scheme in the United Kingdom, estimating the transaction costs at 8 % to 12 % of the investment in lighting and 24 – 36 % of the investment costs for insulation. Falconer and Whitby (2000) analysed the administrative costs of agro-environmental schemes in 8 European countries. The administrative costs varied from 6 % to 87 % of the compensation costs. Nevertheless, the studies are usually not directly comparable. They differ by their focus (different policy programmes), by the method used to study the transaction costs (the choice of at which stage and on which actors the transaction costs are measured), and by the choice of indicator that the transaction costs are compared to (i.e. CO_2 emissions saved, kWh saved, investment or compliance costs). Furthermore, the studies tend to rely on the small statistical sample (L. T. Mundaca et al. 2013).

To sum up, the literature suggests, that the various factors of transaction costs have not been sufficiently addressed. Specifically, the character of their impact on the size and structure of transaction costs of various energy efficiency and RES policy instruments. We address this issue further in the research.

2.3. Ex-post Evaluation

Methods to estimate the expected outcomes of various energy efficiency, RES, and greenhouse gas (GHG) emission schemes and programmes have been elaborated on greatly (Clinch and Healy 2001). They mostly follow the so-called bottom-up approach, which sums up the results of individual projects instead of breaking down general energy efficiency indicators (top-down approach) (more on the two approaches can be found in, e.g. (Abeelen 2013)).

For instance, Karásek and Pavlica (2016) evaluated the expected outcomes of the Czech Green Savings Programme, using the data from the energy audits of the project applications. Wang and Holmberg (2015) focused on the evaluation of the effectiveness of various retrofitting options of the Swedish building stock.

German National Climate Initiative (Nationale Klimaschutzinitiative) covers a diverse mix of instruments and programmes aiming at greenhouse gas emission reduction. Schumacher et al.

(2013) evaluated a total of 25 types of programmes within the Initiative. They evaluated the impacts of both the financial incentives (leading to direct energy and GHG emissions savings) and soft, information measures. In the former case, they used a mix of approaches mostly based on the standard references and scenarios.

Loch et al. (2015) analysed the impact of consultations on the renovation and modernisation of residential buildings in North Rhine-Westphalia, Germany. They used a questionnaire survey in households that sought the consultation. They used the data on their actual energy consumption before the energy efficiency measures and the information on the type of energy efficiency measure implemented. They did not perform ex-post measurements or checks of the actual energy consumption after the measures have been implemented.

It can be seen that the level of detail and accuracy of the monitoring system of the programmes varies greatly (Le Den et al. 2016). Furthermore, the above studies (and many more), as well as policy evaluators, analyse the ex-ante (expected) outcomes of the programmes. The ex-post evaluations of the real outcomes of such programmes are much less common (Webber, Gouldson, and Kerr 2015; Le Den et al. 2016; Hildén, Jordan, and Rayner 2014). Real, achieved energy savings (or GHG emission reduction) are not usually monitored (Hildén, Jordan, and Rayner 2014), and comparative studies on ex-post evaluation are still missing. It must be noted that this is the case, especially in smaller scale projects. Large-scale projects tend to include ex-post evaluation as one of the most important evaluation indicators (Honzík, Karásek, and Chmel 2014). However, as Hildén, Jordan, and Rayner (2014) note, it remains to be investigated, whether the policies commonly projected to deliver the biggest savings are those that are being the most rigorously evaluated ex-post.

Conversely to the situation in the U.S., where ex-post evaluation is more common (Stern and Vantzis 2014), the lack of ex-post evaluation of the real outcomes of the programmes seems to be a general issue across Europe (Rosenow et al. 2016).

The lack of ex-post monitoring in Europe is surprising given the existing proof and debate on the so-called prebound effect. The prebound effect describes the fact that modelled energy consumption of a building is usually higher than the actual consumption. The difference between the modelled and real consumption averages at about 30 % (Sunikka-Blank and Galvin 2012). This discrepancy then leads to overestimation of the expected energy savings resulting from the (subsidised) energy efficiency measures.

While the fact that the real outcomes of policy measures differ from the ex-ante assumptions is well known, the frequency and depth of ex-post evaluations are still small. One of the directions of academic research (with potentially strong practical policy implications) is to provide background data and analyses of ex-post measurements of the policy instruments. W focused on this aspect in our research.

3. Aims of the Habilitation Thesis

Following the literature review, I identified three main areas in energy efficiency and RES policy evaluation with gaps in the academic debate and knowledge. These areas then form the main aims of the current Habilitation thesis and the core of the research articles included in the thesis.

The main aims are:

1. To properly assess the cost-effectiveness of energy efficiency and RES policy instruments

Together with my co-authors, we offer a systemic approach to the economic evaluation of energy efficiency and (especially) renewable energy sources policy. We focus on the systemic approach to the evaluation of energy biomass policies with potential for replication into other related fields.

2. To investigate the transaction costs of energy efficiency policies and examine the role of various factors on the size and structure of the transaction costs

Specifically, we focus on the role of the actors on the size and structure of the transaction costs of energy efficiency programmes, i.e. to which extent the type of actor in the energy efficiency programme influences the burden of transaction costs.

3. To provide ex-post evaluations of energy efficiency policies and programmes

We focus on examining the prebound effect of energy efficiency subsidy programme and analyse the main reasons behind the differences in expected (ex-ante) and real (ex-post) results.

4. Energy Efficiency and RES Policy Evaluation – Contributions

This section reviews my contributions to the energy efficiency policy evaluation, with a focus on cost-effectiveness calculations, including transaction costs, and the role of ex-post evaluations. The contributions are organised into three subsections below, which reflect the main aims of the thesis. I highlight the main results and conclusions relevant to each of the identified research gaps. Publications included in the thesis appendix relevant to each of the topics are indicated at the end of each subsection.

4.1. Economic Evaluation of Energy Efficiency and RES Policies

Firstly, we assessed the effectiveness of different types of biomass gained as primary or by-product from agricultural land, evaluating all elements of the fuel cycle of energy biomass—from biomass production through energy transformations to uses of specific types of biomass (Knápek et al. 2015).

Subsequently, we took a more systemic approach and tried to combine the three main approaches to cost-effectiveness evaluation (supply chain analysis, competitiveness with other crops, and the substitutes) in one general model. The general model enables the policy makers and researchers to make decisions on the growth in production of biomass for energy purposes, to estimate the 'real' biomass contribution to the primary energy sources, based on its market competitiveness, and to formulate the cost-effective policy options for intentionally grown biomass. We demonstrated the functioning of our model on a case example of the Czech Republic.

We came up with a 'decision-making triangle'. The first vertex of the triangle is formed by the price for growing biomass for energy purposes (referred to as c_{min}). The price of intentionally grown biomass c_{min} must provide the investor with the required return on invested capital over the project lifetime. The second vertex of the decision-making triangle is defined as the price of biomass (c_{alt}) which ensures the same net economic effect for the farmer as the conventional commodities (e.g. barley, wheat, etc.), taking into account agriculture subsidies for conventional production.

The first two vertices define the bottom limit for the price of energy biomass intentionally grown on agriculture land (c_{bot_lim}).

$$C_{bot\_lim} = \max(c_{min}; c_{alt}) \qquad (1),$$

where

c_{min} is the minimum price of grown biomass for energy purposes that assures an adequate rate of return for investors [EUR/GJ]; and

c_{alt} is the price of grown biomass for energy purposes that assures the same economic benefit as conventional agricultural production [EUR/GJ].

The third aspect that influences the energy biomass price (and the third vertex of the triangle) is consumers' willingness to accept the price of biomass as a substitute for conventional fuels. Consumers will accept (at maximum) such biomass price (c_{subs}) that will assure the same economic effect from the power and/or heat production as it is from the utilization of other (conventional) fuels.

The results of the case study then revealed that under current conditions, farmers are not likely to switch from conventional crops to energy biomass (c_{alt} in all cases higher than c_{min}). Furthermore, the energy biomass for local needs is not competitive as a substitute for brown coal ($c_{subs,sh}$). In the case of co-firing in large power stations, energy biomass could be competitive (i.e. c_{min} meets $c_{subs,pg}$).

As for the energy efficiency policy, we examined the status of the existing light emitting diode (LED) pilot actions in Europe as of 2011, analysing 106 LED test cases from 17 European countries. The article represented the first-time overview of its kind of the state of the art of LED pilot projects. Projects from the public and commercial sectors formed the focus of the article. We paid special attention to the energy savings of the pilot projects and evaluation of the cost-effectiveness of the projects.

At the time of writing the article, the LEDs have been emerging, quickly spreading technology. A typical application for LEDs would be outdoor public lighting installations. However, the costs of the technology were quite high. In general, the payback was higher for outdoor (public lighting) installations than for indoor (mostly commercial) applications.

Importantly, the research showed that the respondents often preferred the unquantified (or unquantifiable) co-benefits of the installations, such as road safety for traffic lights (and compliance with standards, which was often not the case for the existing lighting solutions), no UV radiation, indoor and outdoor lighting quality, indoor ambience, and atmosphere, variability in the design of LED applications, and environmental benefits.

The results have been published in (Knápek et al. 2015), (Knápek et al. 2017), and (Valentová, Quicheron, and Bertoldi 2015). All three articles have been cited further.

4.2. Factors of Transaction Costs in Energy Efficiency Programmes

Using qualitative and quantitative analysis, we studied the transaction costs of two major energy efficiency subsidy programmes in the Czech Republic. Based on the current state of knowledge on the factors influencing the transaction costs, the research question has been translated into two main research hypotheses. The first hypothesis of the article was that the size of transaction costs is not fixed and depends on the size of the subsidised project. The second hypothesis stated that the level and structure of transaction costs differ according to the type of actor carrying out the project.

We examined the transaction costs in two particular subsidy programmes financed from the European Cohesion policy in the period 2007 – 2013: Operational Programme Environment (OP E, specifically Priority axis 3 focused on energy efficiency) and Operational Programme Enterprise and Innovation (specifically the ECO-ENERGY programme).

The data were collected based on mixed method research. In line with this method, firstly qualitative research provided initial ("exploratory") information on the given topic. Based on this knowledge, quantitative research was carried out, testing, generalising, and supporting the initial findings. After desk research of the primary documents of the programmes, semi-standardised in-depth interviews with subsidy recipients and representatives of the administrative bodies were carried out. Thirdly, based on the interviews, a questionnaire was distributed among subsidy recipients. In total, we contacted 463 subsidy recipients and 125 of them fully completed the questionnaire

The results suggested that the transaction costs in energy efficiency subsidy programmes are of non-negligible levels, altogether averaging at 11 % – 14 % of the total subsidy allocation, with the most time and cost intensive parts of the administration process being the application submittal and public tenders.

The results are comparable in their order of magnitude to the conclusions of available international analyses (even though due to methodological differences the studies tend to be rather case-specific). In line with other studies, we found that the size of transaction costs was closely related to the size of the project. For smaller projects, there seemed to be directly proportionate relation whereas for bigger projects economies of scale apply and the total burden of transaction costs decreases.

Other factors being the same, in our case study, the type of actor did not show to play the major role in the size of transaction costs. However, some differences could be traced in how the two actors negotiate for external services for implementing the projects. For smaller projects, which formed most of the sample and the whole population in the programme, private companies seemed to be more effective, while for bigger projects (over EUR 300,000) public entities proved more efficient. For both types of actors, transaction costs mostly arise in the preparatory phase of the application and tender procedures.

The results have been published in (Valentová, Lízal, and Knápek 2018).

4.3. Ex-post Evaluation of Energy Efficiency Policies

In 2011, we evaluated the achievements of the GreenBuilding Programme. In our analysis, we focused on the energy savings achieved and the energy efficiency measures implemented in the participating buildings. The European Commission launched the programme in early 2006. It aimed at improving the energy efficiency and expanding the integration of renewable energies in non-residential buildings in Europe on a voluntary basis. The programme encouraged owners of non-residential buildings to implement cost-effective measures which enhanced the energy efficiency of their buildings in one or more equipment systems.

The evaluation was based on the data submitted by the Partners in their reports. The data provided by the Partners underwent a double quality and consistency check, firstly by the National Contact Points for inconsistencies, and then by the Programme administrator (the Joint Research Centre (JRC), who reviewed the reports before granting the building and the organisation the status of GreenBuilding Partner.

Recently, we approached the policy evaluation from a different angle, and specifically aimed at filling the gap of ex-post evaluations. We evaluated the real outcomes of the major subsidy programme in the Czech Republic, the Green Savings Programme. By investigating the 206 projects ex-post, we offered a unique insight into the real outcomes of the energy efficiency measures and the whole programme.

In our research, a total of 206 measures was inspected in 124 projects, including combinations of measures. We determined the real energy consumption before and after the implementation of the measures based on energy invoices (and other relevant available data). Like that, the comparison of ex-ante and ex-post CO_2 emission reduction could be performed at 70 projects (56 % success rate). In case the ex-post calculation could not be made, the reasons were mostly the unavailability of invoices, low level of detail or the fact that the buildings were not inhabited yet or for a sufficient amount of time (in case of new buildings). Also, semi-structured interviews were carried out with the household owners to examine further relevant factors that may have influenced the final energy consumption in the inspected objects (such as the use of the building, thermal comfort, occupancy of the building, additional heat sources, and other).

The inspections showed that there is a significant difference between the ex-ante CO_2 emission reduction and ex-post results (25 % on average). The reasons were partly methodical (e.g. calculation methods and norms used for calculation of specific heat demand, inability to cover other heat sources such as fireplaces), but mostl could be attributed to the behavioural factors in the respective buildings. Higher thermal comfort than in the ex-ante calculations lead to lower real savings. Similarly, occupancy or patterns of use of the buildings had a high impact on resulting savings. If the buildings were not fully used for long-term, the measures had a highly lower positive impact.

We demonstrated that the ex-post evaluation should be a standard part of the energy efficiency programme. Even if the supported projects are small (family houses or building technologies), a sample of applications (units of per cent of the whole population) should be selected where the ex-post evaluation would be carried out. Importantly, such research should be independent of the inspections implemented for legal requirements (avoiding deceptions), in order to ensure a useful cooperation between the building owners and the research team.

In reality, the follow-up programme, the New Green Savings Programme running since 2013 involves a significantly lower number of households (around 14 000 as of 2018). The programme setting does not envisage any changes regarding ex-post evaluation.

The results have been published in (Valentová and Bertoldi 2011) and (Valentová, Karásek, and Knápek 2018). Since its publication, the former article has served as a point of reference to a number of research articles.

5. Conclusions and Further Research

A significant amount of financing has been available for improvements in energy efficiency and RES in all sectors of the economy in recent years. Operational programmes have so far represented the most important source of funding in the Czech Republic: over 1 billion EUR was dedicated specifically to energy efficiency and RES measures solely in the programming period 2007 – 2013, so about 5% of the total allocation. In 2014 – 2020 the funds to energy efficiency increased to 2.4 billion EUR (about 10 % of total allocation in the Czech Republic). However, monitoring and evaluation of the programmes remain often inadequate.

Furthermore, it starts to be clear that the targets on energy efficiency progress as set by the Energy Efficiency Directive, are very likely not to be met (esp. the ones brought by Art. 7, demanding that new savings of 1.5% are achieved each year by 2020) (European Parliament and Council 2012). New approaches to boosting energy efficiency and RES investments are sought by the policymakers (Ministry of Industry and Trade of the Czech Republic 2017).

Following our research and findings so far and in the light of the above directions in energy efficiency policy, the future paths for my research can be categorised into three mains streams:

- **Exploring the potential of new financial instruments to support energy efficiency**

  This research path includes an understanding of the financial flows currently being invested into energy- and climate-related measures, estimating investment needs to reach national (and EU) climate and energy goals, and investigating the options to mobilising the corresponding investments.

- **Economic evaluation of energy efficiency and RES programmes**

  Further research will entail exploring the learning effect on transaction costs in the energy efficiency and RES policies, and building the transaction costs evaluation in the overall assessment of the energy efficiency and RES programmes.

- **Investigating the non-energy benefits of energy efficiency and RES measures**

  Multiple benefits of energy efficiency and RES measures become more and more important as part of the cost-benefit analysis. The methods to estimate them are still under development and data are inadequately covered.

REFERENCES

Abeelen, Christiaan. 2013. 'From Top-down to Bottom-up; Two Ways to Monitor Energy-Efficiency in Dutch Voluntary Agreements'. In *Eceee 2013 Summer Study on Energy Efficiency: Rethink, Renew, Restart*, 1953–62. Belambra Les Criques, Toulon/Hyères, France. https://www.eceee.org/library/conference_proceedings/eceee_Summer_Studies/2013/7-monitoring-and-evaluation/from-top-down-to-bottom-up-two-ways-to-monitor-energy-efficiency-in-dutch-voluntary-agreements/.

Ahonen, Hanna-Mari, and Kari Hämekoski. 2005. 'Transaction Costs under the Finnish CDM/JI Pilot Programme'. Discussion paper No. 12. Helsinki: University of Helsinki.

Applica, and Ismeri Europa. 2016. 'Ex Post Evaluation of Cohesion Policy Programmes 2007-2013, Focusing on the European Regional Development Fund (ERDF) and the Cohesion Fund (CF). WP1: Synthesis Report'. Report for the European Commission. http://ec.europa.eu/regional_policy/en/policy/evaluations/ec/2007-2013/#1.

Bakam, I, B.B. Balana, and R. Matthews. 2012. 'Cost-Effectiveness Analysis of Policy Instruments for Greenhouse Gas Emission Mitigation in the Agricultural Sector.' *Journal of Environmental Management* 112 (December): 33–44. https://doi.org/10.1016/j.jenvman.2012.07.001.

Björkqvist, Olof, and Clas-Otto Wene. 1993. 'A Study of the Transaction Costs for Energy Investments in the Residential Sector'. In *Proceedings of the 1993 Summer Study*, 23–30. Stockholm: The European Council for an Energy Efficient Economy (ECEEE). http://www.eceee.org/library/conference_proceedings/eceee_Summer_Studies/1993/Panel_3/p3_3.

Cambero, Claudia, and Taraneh Sowlati. 2014. 'Assessment and Optimization of Forest Biomass Supply Chains from Economic, Social and Environmental Perspectives – A Review of Literature'. *Renewable and Sustainable Energy Reviews* 36 (August): 62–73. https://doi.org/10.1016/j.rser.2014.04.041.

Campbell, Nina. 2014. 'Capturing the Multiple Benefits of Energy Efficiency'. International Energy Agency.

Cansino, José M., María del P. Pablo-Romero, Rocío Román, and Rocío Yñiguez. 2011. 'Promoting Renewable Energy Sources for Heating and Cooling in EU-27 Countries'. *Energy Policy* 39 (6): 3803–12. https://doi.org/10.1016/j.enpol.2011.04.010.

Cheung, Steven N.s. 1998. 'The Transaction Costs Paradigm 1998 Presidential Address Western Economic Association'. *Economic Inquiry* 36 (4): 514–21. https://doi.org/10.1111/j.1465-7295.1998.tb01733.x.

Clinch, J. Peter, and John D. Healy. 2001. 'Cost-Benefit Analysis of Domestic Energy Efficiency'. *Energy Policy* 29 (2): 113–24. https://doi.org/10.1016/S0301-4215(00)00110-5.

Coggan, Anthea, Edwin Buitelaar, Stuart Whitten, and Jeff Bennett. 2013. 'Factors That Influence Transaction Costs in Development Offsets: Who Bears What and Why?' *Ecological Economics*, Transaction Costs and Environmental Policy, 88 (April): 222–31. https://doi.org/10.1016/j.ecolecon.2012.12.007.

De la Rue du Can, S., G. Leventis, A. Phadke, and A. Gopal. 2014. 'Design of Incentive Programs for Accelerating Penetration of Energy-Efficient Appliances'. *Energy Policy* 72: 56–66. https://doi.org/10.1016/j.enpol.2014.04.035.

Ecofys. 2017. ‘2030 Energy Efficiency Target Ambition. Critical Review of the European Commission Assessment for the Clean Energy For All Europeans Package. Towards a Cost-Benefit Analysis.’ https://www.ecofys.com/files/files/ecofys-ces-2017-impact-assessment-eed.pdf.

Environmental Protection Agency. 2008. ‘Understanding Cost-Effectiveness of Energy Effi Ciency Programs: Best Practices, Technical Methods, and Emerging Issues for Policy-Makers’.

European Commission. 2010. ‘COMMUNICATION FROM THE COMMISSION EUROPE 2020. A Strategy for Smart, Sustainable and Inclusive Growth’. COM(2010) 2020 final. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2010:2020:FIN:EN:PDF.

———. 2016. ‘ANNEX Accelerating Clean Energy in Buildings to the COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL,THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE, THE COMMITTEE OF THE REGIONS AND THE EUROPEAN INVESTMENT BANK Clean Energy For All Europeans’. COM(2016) 860 final.

European Parliament and Council. 2009. ‘Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the Promotion of the Use of Energy from Renewable Sources and Amending and Subsequently Repealing Directives 2001/77/EC and 2003/30/EC’. https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:32009L0028.

———. 2012. ‘DIRECTIVE 2012/27/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 25 October 2012 on Energy Efficiency, Amending Directives 2009/125/EC and 2010/30/EU and Repealing Directives 2004/8/EC and 2006/32/EC’. Official Journal of the European Union. http://eur-lex.europa.eu/legal-content/en/TXT/?uri=celex%3A32012L0027.

Falconer, Katherine, Pierre Dupraz, and Martin Whitby. 2001. ‘An Investigation of Policy Administrative Costs Using Panel Data for the English Environmentally Sensitive Areas’. *Journal of Agricultural Economics* 52 (1): 83–103. https://doi.org/10.1111/j.1477-9552.2001.tb00911.x.

Falconer, Katherine, and Martin Whitby. 2000. ‘Untangling Red Tape: Scheme Administration and the Invisible Costs of European Agri-Environmental Policy’. *European Environment* 10 (4): 193–203. https://doi.org/10.1002/1099-0976(200007/08)10:4<193::AID-EET231>3.0.CO;2-D.

Fazio, S, L Barbanti, and G Venturi. 2009. ‘Energy and Economic Balances of Different Dedicated Energy Crops’. In *Proceedings of the 17th EU Biomass Conference and Exhibition*. Florence: ETA-Florence. http://www.eubce.com/conference/publications-of-papers/proceedings.html.

Furubotn, Eirik Grundtvig, and Rudolf Richter. 2000. *Institutions and Economic Theory: The Contribution of the New Institutional Economics*. University of Michigan Press.

Gasol, Carles M., Filippo Brun, Angela Mosso, Joan Rieradevall, and Xavier Gabarrell. 2010. ‘Economic Assessment and Comparison of Acacia Energy Crop with Annual Traditional Crops in Southern Europe’. *Energy Policy* 38 (1): 592–97. https://doi.org/10.1016/j.enpol.2009.10.011.

Gawel, Erik, Paul Lehmann, Alexandra Purkus, Patrik Söderholm, and Katherina Witte. 2017. ‘Rationales for Technology-Specific RES Support and Their Relevance for German Policy’. *Energy Policy* 102 (March): 16–26. https://doi.org/10.1016/j.enpol.2016.12.007.

Harmsen, Robert. 2014. ‘Interpreting Cost-Effectiveness: Target Definitions versus Policy Objectives’. In . Berlin.

Hauk, Sebastian, Thomas Knoke, and Stefan Wittkopf. 2014. ‘Economic Evaluation of Short Rotation Coppice Systems for Energy from Biomass—A Review’. *Renewable and Sustainable Energy Reviews* 29 (January): 435–48. https://doi.org/10.1016/j.rser.2013.08.103.

Hildén, Mikael, Andrew Jordan, and Tim Rayner. 2014. ‘Climate Policy Innovation: Developing an Evaluation Perspective’. *Environmental Politics* 23 (5): 884–905. https://doi.org/10.1080/09644016.2014.924205.

Hilst, F van der, V Dornburg, A.P.C Faaij, J.P.M Sanders, W Ebersen, and W Turkenburg. 2008. ‘Economic and Energetic Performance of Energy Crops: An Analyis for the Nothern Region of the Netherlands’. In *Proceedings of the 16th EU Biomass Conference and Exhibition*, 2585–90. Valencia: ETA-Florence.

Honzík, Miroslav, Jiří Karásek, and Petr Chmel. 2014. ‘Basis for the National Action Plan for Ministry of Industry and Trade’. Prague: SEVEn.

Huber, Claus, Lisa Ryan, Brian Ó Gallachóir, Gustav Resch, Katrina Polaski, and Morgan Bazilian. 2007. ‘Economic Modelling of Price Support Mechanisms for Renewable Energy: Case Study on Ireland’. *Energy Policy* 35 (2): 1172–85. https://doi.org/10.1016/j.enpol.2006.01.025.

Jaraité, JŪRATĖ, Frank Convery, and Corrado Di Maria. 2010. ‘Transaction Costs for Firms in the EU ETS: Lessons from Ireland’. *Climate Policy* 10 (2): 190–215. https://doi.org/10.3763/cpol.2009.0659.

Karásek, Jiří, and Jaroslav Pavlica. 2016. ‘Green Investment Scheme: Experience and Results in the Czech Republic’. *Energy Policy* 90: 121–30. https://doi.org/10.1016/j.enpol.2015.12.020.

Kasmioui, Ouafik El, and Reinhart Ceulemans. 2013. ‘Financial Analysis of the Cultivation of Short Rotation Woody Crops for Bioenergy in Belgium: Barriers and Opportunities’. *BioEnergy Research* 6 (1): 336–50. https://doi.org/10.1007/s12155-012-9262-7.

Kiss, Bernadett. 2016. ‘Exploring Transaction Costs in Passive House-Oriented Retrofitting’. *Journal of Cleaner Production*, Advancing Sustainable Solutions: An Interdisciplinary and Collaborative Research Agenda, 123 (June): 65–76. https://doi.org/10.1016/j.jclepro.2015.09.035.

Klessmann, C., C. Nabe, and K. Burges. 2008. ‘Pros and Cons of Exposing Renewables to Electricity Market Risks-A Comparison of the Market Integration Approaches in Germany, Spain, and the UK’. *Energy Policy* 36 (10): 3646–61. https://doi.org/10.1016/j.enpol.2008.06.022.

Knápek, Jaroslav, Tomáš Králík, Michaela Valentová, and Tomáš Vořříšek. 2015. ‘Effectiveness of Biomass for Energy Purposes: A Fuel Cycle Approach’. *Wiley Interdisciplinary Reviews: Energy and Environment* 4 (6): 575–86. https://doi.org/10.1002/wene.164.

Knápek, Jaroslav, Kamila Vávrová, Michaela Valentová, Jiří Vašíček, and Tomáš Králík. 2017. ‘Energy Biomass Competitiveness—Three Different Views on Biomass Price’. *Wiley Interdisciplinary Reviews: Energy and Environment* 6 (6): e261. https://doi.org/10.1002/wene.261.

Krasuska, Ewa, and Håkan Rosenqvist. 2012. ‘Economics of Energy Crops in Poland Today and in the Future’. *Biomass and Bioenergy*, Overcoming Barriers to Bioenergy: Outcomes of the Bioenergy Network of Excellence 2003 – 2009, 38 (March): 23–33. https://doi.org/10.1016/j.biombioe.2011.09.011.

Labanca, Nicola, and Paolo Bertoldi. 2017. *Workshop on Annual Energy Savings Generated through Energy Efficiency Obligation Schemes and Alternative Measures Implemented under EED Article 7: Summary of the Topics Discussed*. Publications Office of the European Union. https://ec.europa.eu/jrc/en/publication/workshop-annual-energy-savings-generated-through-energy-efficiency-obligation-schemes-and.

Le Den, Xavier, Miguel Riviere, Franziska Lessman, Martin Nesbit, Kamila Paquel, and Andrea Illes. 2016. ‘Evaluating EU Cohesion Policy Funding for Energy Efficiency Investments in Public and Residential Buildings Across EU Member States’. In . Amsterdam. http://www.ieppec.org/wp-content/uploads/2016/05/Paper-Leden-1.pdf.

Lee, Kangil, and Taek-Whan Han. 2016. ‘How Vulnerable Is the Emissions Market to Transaction Costs?: An ABMS Approach’. *Energy Policy* 90 (March): 273–86. https://doi.org/10.1016/j.enpol.2015.12.013.

Loch, Reinhard, Martin Steinestel, and Udo Sieverding. 2015. ‘Evaluation of On-Site Energy Consultations Concerning Energetic Modernisation of Private Homes in North Rhine-Westphalia (NRW), Germany’. In *ECEEE 2015 Summer Study - First Fuel Now*, 1725–33.

McCann, Laura. 2013. 'Transaction Costs and Environmental Policy Design'. *Ecological Economics*, Transaction Costs and Environmental Policy, 88 (April): 253–62. https://doi.org/10.1016/j.ecolecon.2012.12.012.

McCann, Laura, Bonnie Colby, K. William Easter, Alexander Kasterine, and K. V. Kuperan. 2005. 'Transaction Cost Measurement for Evaluating Environmental Policies'. *Ecological Economics* 52 (4): 527–42. https://doi.org/10.1016/j.ecolecon.2004.08.002.

McNeil, Michael A., and Nicholas Bojda. 2012. 'Cost-Effectiveness of High-Efficiency Appliances in the U.S. Residential Sector: A Case Study'. *Energy Policy* 45 (June): 33–42. https://doi.org/10.1016/j.enpol.2011.12.050.

Michaelowa, Axel, and Frank Jotzo. 2005. 'Transaction Costs, Institutional Rigidities and the Size of the Clean Development Mechanism'. *Energy Policy* 33 (4): 511–23. https://doi.org/10.1016/j.enpol.2003.08.016.

Michaelowa, Axel, Marcus Stronzik, Frauke Eckermann, and Alistair Hunt. 2003. 'Transaction Costs of the Kyoto Mechanisms'. *Climate Policy* 3 (3): 261–78. https://doi.org/10.1016/S1469-3062(03)00061-5.

Ministry of Industry and Trade of the Czech Republic. 2017. 'Update of the National Energy Efficiency Action Plan of the Czech Republic'.

Mundaca, Luis. 2007. 'Transaction Costs of Tradable White Certificate Schemes: The Energy Efficiency Commitment as Case Study'. *Energy Policy* 35 (8): 4340–54. https://doi.org/10.1016/j.enpol.2007.02.029.

Mundaca, Luis T., Mathilde Mansoz, Lena Neij, and Govinda R. Timilsina. 2013. 'Transaction Costs Analysis of Low-Carbon Technologies'. *Climate Policy* 13 (4): 490–513. https://doi.org/10.1080/14693062.2013.781452.

Musole, Maliti. 2009. 'Property Rights, Transaction Costs and Institutional Change: Conceptual Framework and Literature Review'. *Progress in Planning*, Property Rights, Transaction Costs and Institutional Change: Conceptual Framework and Literature Review, 71 (2): 43–85. https://doi.org/10.1016/j.progress.2008.09.002.

Nasiri, Fuzhan, Fereshteh Mafakheri, Dotun Adebanjo, and Fariborz Haghighat. 2016. 'Modeling and Analysis of Renewable Heat Integration into Non-Domestic Buildings - The Case of Biomass Boilers: A Whole Life Asset-Supply Chain Management Approach'. *Biomass and Bioenergy* 95 (December): 244–56. https://doi.org/10.1016/j.biombioe.2016.10.018.

North, Douglass C. 1990. *Institutions, Institutional Change and Economic Performance*. Cambridge University Press. https://www.goodreads.com/work/best_book/727869-institutions-institutional-change-and-economic-performance-political-e.

Ostertag, Katrin. 1999. 'Transaction Costs of Raising Energy Efficiency'. In . Washington D.C., USA. http://www.isi.fraunhofer.de/isi-wAssets/docs/x/de/publikationen/econserv.pdf.

———. 2003. *No-Regret Potentials in Energy Conservation - An Analysis of Their Relevance, Size and Determinants*. Technology, Innovation and Policy (ISI) 15. Heidelberg: Physica-Verlag. http://www.springer.com/us/book/9783790815399.

Ramboll, Management Consulting A/S, and Institute for European Environmental Policy. 2016. 'Energy Efficiency in Public and Residential Buildings Final Report. Work Package 8. Ex Post Evaluation of Cohesion Policy Programmes 2007-2013, Focusing on the European Regional Development Fund (ERDF) and the Cohesion Fund (CF)'. Luxembourg: Publications Office of the European Union.

Rao, P.K. 2003. *The Economics of Transaction Costs*. Hampshire and New York: Palgrave Macmillan.

Reddy, Amulya K. N. 1991. 'Barriers to Improvements in Energy Efficiency'. *Energy Policy*, Climate change - country case studies, 19 (10): 953–61. https://doi.org/10.1016/0301-4215(91)90115-5.

Rietbergen, Martijn G., and Kornelis Blok. 2010. 'Setting SMART Targets for Industrial Energy Use and Industrial Energy Efficiency'. *Energy Policy* 38 (8): 4339–54. https://doi.org/10.1016/j.enpol.2010.03.062.

Río, Pablo del, and Emilio Cerdá. 2014. 'The Policy Implications of the Different Interpretations of the Cost-Effectiveness of Renewable Electricity Support'. *Energy Policy* 64 (January): 364–72. https://doi.org/10.1016/j.enpol.2013.08.096.

Rosenow, Jan, Cor Leguijt, Zsuzsanna Pato, Nick Eyre, and Tina Fawcet. 2016. 'An Ex-Ante Evaluation of the EU Energy Efficiency Directive - Article 7'. *Economics of Energy & Environmental Policy* 5 (2). https://doi.org/10.5547/2160-5890.5.2.jros.

Sanstad, Alan H., and Richard B. Howarth. 1994. '"Normal" Markets, Market Imperfections and Energy Efficiency'. *Energy Policy*, Markets for energy efficiency, 22 (10): 811–18. https://doi.org/10.1016/0301-4215(94)90139-2.

Sathaye, Jayant, and Scott Murtishaw. 2004. 'Market Failures, Consumer Preferences, and Transaction Costs in Energy Efficiency Purchase Decisions'. LBNL-57318. Lawrence Berkeley National Laboratory. https://escholarship.org/uc/item/6718v9dw.

Schofield, Norman, Gonzalo Caballero, and Daniel Kselman, eds. 2013. *Advances in Political Economy - Institutions, Modelling and Empirical Analysis*. Springer-Verlag Berlin Heidelberg. http://www.springer.com/br/book/9783642352386.

Schumacher, Katja, Julia Repenning, Christine Woerlen, Sara Riesenberg, Christina Heldwein, Kerstin Tews, Maria Rosaria di Nucci, Benjamin Goerlach, Max Gruenig, and Hans - Joachim Ziesing. 2013. 'Evaluation of the German National Climate Initiative: Lessons Learned and Steps Ahead'. In , 1935–46.

Sgroi, Filippo, Anna Maria Di Trapani, Mario Foderà, Riccardo Testa, and Salvatore Tudisca. 2015. 'Economic Assessment of Eucalyptus (Spp.) for Biomass Production as Alternative Crop in Southern Italy'. *Renewable and Sustainable Energy Reviews* 44 (April): 614–19. https://doi.org/10.1016/j.rser.2015.01.032.

Shahab, Sina, J. Peter Clinch, and Eoin O'Neill. 2018. 'Accounting for Transaction Costs in Planning Policy Evaluation'. *Land Use Policy* 70 (January): 263–72. https://doi.org/10.1016/j.landusepol.2017.09.028.

Stern, Frank, and Dimitris Vantzis. 2014. 'Protocols for Evaluating Energy Efficiency – Both Sides of the Atlantic'. In . Berlin.

Styles, David, Fiona Thorne, and Michael B. Jones. 2008. 'Energy Crops in Ireland: An Economic Comparison of Willow and Miscanthus Production with Conventional Farming Systems'. *Biomass and Bioenergy* 32 (5): 407–21. https://doi.org/10.1016/j.biombioe.2007.10.012.

Sunikka-Blank, Minna, and Ray Galvin. 2012. 'Introducing the Prebound Effect: The Gap between Performance and Actual Energy Consumption'. *Building Research & Information* 40 (3): 260–73. https://doi.org/10.1080/09613218.2012.690952.

Valentová, Michaela, and Paolo Bertoldi. 2011. 'Evaluation of the GreenBuilding Programme'. *Energy and Buildings* 43 (8): 1875–83. https://doi.org/10.1016/j.enbuild.2011.03.028.

Valentová, Michaela, Jiří Karásek, and Jaroslav Knápek. 2018. 'Ex-Post Evaluation of Energy Efficiency Programmes: Case Study of Czech Green Investment Scheme'. *Wiley Interdisciplinary Reviews: Energy and Environment*, Forthcoming.

Valentová, Michaela, Lubomír Lízal, and Jaroslav Knápek. 2018. 'Designing Energy Efficiency Subsidy Programmes: The Factors of Transaction Costs'. *Energy Policy* 120 (September): 382–91. https://doi.org/10.1016/j.enpol.2018.04.055.
Valentová, Michaela, Michel Quicheron, and Paolo Bertoldi. 2015. 'LED Projects and Economic Test Cases in Europe'. *International Journal of Green Energy* 12 (8): 843–51. https://doi.org/10.1080/15435075.2014.887568.
Wang, Qian, and Sture Holmberg. 2015. 'A Methodology to Assess Energy-Demand Savings and Cost Effectiveness of Retrofitting in Existing Swedish Residential Buildings'. *Sustainable Cities and Society* 14 (February): 254–66. https://doi.org/10.1016/j.scs.2014.10.002.
Webber, Phil, Andy Gouldson, and Niall Kerr. 2015. 'The Impacts of Household Retrofit and Domestic Energy Efficiency Schemes: A Large Scale, Ex Post Evaluation'. *Energy Policy* 84 (September): 35–43. https://doi.org/10.1016/j.enpol.2015.04.020.
Yushchenko, Alisa, and Martin Kumar Patel. 2017. 'Cost-Effectiveness of Energy Efficiency Programs: How to Better Understand and Improve from Multiple Stakeholder Perspectives?' *Energy Policy* 108 (September): 538–50. https://doi.org/10.1016/j.enpol.2017.06.015.

ANNEXES

The following publications are included in the annex, listed in the order they appear in the thesis:

Annex 1

'Effectiveness of Biomass for Energy Purposes: A Fuel Cycle Approach' *(Knápek et al. 2015)*

Advanced Review

Effectiveness of biomass for energy purposes: a fuel cycle approach

Jaroslav Knápek,[1*] Tomáš Králík,[1] Michaela Valentová[1] and Tomáš Voříšek[2]

The article presents a methodology that allows the complex evaluation of the energy and economic effectiveness of the different kinds of biomass providing, processing and utilization for energy purposes. The methodology is based on identification of the whole fuel cycle for the individual types of grown biomass and conversion technologies used for production of end-use energy products (such as biomethane, liquid biofuels, electricity, and heat). The evaluation of energy efficiency is based on the calculation of the net energy effect resulting from the use of 1 ha of agricultural land to grow biomass for energy purposes respecting differences in biomass fuel cycles due to differences in biomass production, conversion technologies, and end-use energy products. Evaluation of the economic effectiveness of biomass utilization combines efficiency of biomass planting, conversion technologies, and the economic parameters of the individual elements of the fuel cycle. The application of the method is demonstrated on selected cases of biomass fuel cycles in the conditions of the Czech Republic. The methodology can serve as the groundwork for identifying the most effective strategies of biomass utilization for the energy purposes with respect to the limitation of agricultural land availability and the economic effectiveness of end-use energy products providing.

How to cite this article:
WIREs Energy Environ 2015, 4:575–586. doi: 10.1002/wene.164

INTRODUCTION

Renewable energy sources play the important and growing role in EU energy mix. In 2012, the total amount of renewable energies in EU-28 exceeded 7400 PJ, which was more than 22% of total primary energy sources consumed by EU-28. Biomass (in its all forms) currently plays the key role in the portfolio of renewable energies contributing app. 2/3 to total sum of renewable energies.[1]

Biomass is a renewable energy source with the highest potential for growth both in mid-term (until 2020) and long-term (until 2050) in the Czech Republic as well as the EU.[2–4]

*Correspondence to: knapek@fel.cvut.cz

[1]Department of Economy, Management and Humanities, Faculty of Electrical Engineering, Czech Technical University in Prague, Praha, Czech Republic

[2]SEVEn, The Energy Efficiency Center, Praha, Czech Republic

Conflict of interest: The authors have declared no conflicts of interest for this article.

National Renewable Action Plans (NREAPs) of the EU member states assume that biomass consumption in the EU as a whole only for heating and cooling will increase by 46% between the years 2010 and 2020.[5] Biomass also plays the important role in power generation. According to NREAPs, a 2.24 times increase of biomass consumption in the EU is expected in 2010–2020. Biomass plays an even more important role in the expected RES portfolio in the Czech Republic. The Czech NREAP, e.g., expects an increase of the biomass share in RES power generation from 36% in 2010 to 53% in 2020. The updated Czech Energy Policy[4] from 2012 assumes an increase of biomass utilization as the primary energy source from ca 100 PJ in 2010, to 145 PJ in 2020, and ca 210 PJ in 2040.

However, the biomass sources that are easily exploitable, such as waste and residual biomass, are fast depleted and their potential is almost attained. Therefore, mid-term and esp. long-term aims defined both on the EU and the Czech levels can be only obtained through the development of intentionally grown biomass on agricultural land.

When developing a strategy for biomass development the most economically and energetically efficient options should be searched for. However, biomass is a heterogeneous category, and different ways and needs for its production, transformation and use need to be respected.[6]

EFFECTIVENESS OF BIOMASS UTILIZATION FOR ENERGY PURPOSES

There have been a number of studies that evaluate energy and economic effectiveness of energy biomass. However, they tend to focus only on a selected part of energy biomass fuel cycle. Using a full step approach,[7] most of the studies appear to focus on evaluating the costs of biomass production (e.g., Refs 6, 8, and 9). Krasuska and Rosenqvist,[9] e.g., evaluate the economics of biomass production from energy crops in Poland (willow, Miscanthus and triticale) and further compare them to conventional crops.

The results presented in the above studies can hardly be directly compared, due to different methodologies used in analyzing economic effectiveness of intentionally planted biomass. The studies also use a simplified calculation of specific costs of biomass production—referring to a 'typical' year and 'typical' biomass yields (e.g., Refs 10 and 11). In case of perennial crops, the time value of money, inflation, projects lifetime, and time dynamics of the yield curves of the energy crops are not taken into account. A thorough discussion on different approaches to biomass production costs can be found, among others, in the study by Havlíčková, Weger and Knápek.[12]

A number of studies also evaluated the costs of supply of biomass to municipalities (e.g., harvesting and transport costs Refs 7, 13, and 14). For instance, Kamimura et al.[13] estimate the wood biomass supply for energy (focusing on supply costs) in Japanese regions. The costs include harvesting and transportation systems (costs of forwarding, chipping, and transportation).

Alternatively, the studies analyze the last step of energy biomass fuel cycle, i.e., different conversion processes, their energy and economic effectiveness, but disregard different methods of production (e.g., Refs 15 and 16).

Only a few studies actually evaluate the whole cycle of the biomass, from its production through harvesting, transport, and conversion processes to end-use energy products. For instance, Hoogwijk et al.[11] evaluate the cost-supply curve of biomass, i.e., focusing on the production costs of energy biomass and consequently on costs of 'secondary' biomass energy (bio-electricity and liquid fuels).

This study argues that to correctly evaluate energy biomass effectiveness (both energy and economic), the whole chain of energy conversions should be respected, from biomass production on agricultural land through all processes (e.g., transportation, storage, pelleting, anaerobic digestion, biomass gasification, electricity generation, biogas upgrade to methane, etc.) that were needed to obtain any given kind of end-use energy product.

The practical application of the developed method to evaluate the effectiveness of individual kinds of biomass production and utilization for energy purposes is illustrated in detail on several case studies of energy biomass cycle in the conditions of the Czech Republic.

Scope of the Study

The main aim of the study is to assess effectiveness of different types of biomass gained as primary or byproduct from agricultural land, evaluating all elements of the fuel cycle of energy biomass—from biomass production through energy transformations to uses of specific types of biomass. The evaluation of effectiveness is related to the only scarce resource there actually is—(agricultural) land. The study provides methodical guideline that makes it possible to determine how to allocate effectively the scarce resource, land, to energy biomass from the system point of view, i.e., how to select economically effective strategies for systemic energy biomass development. The method is based on internal costs only and does not include potential externalities.

Biomass is a heterogeneous category that covers different types of biomass varying by their production methods (intentional planting, residual biomass from wood or from agriculture, etc.), by technologies used for their processing and by final energy products at the end of the cycle. As discussed in the introduction, in most developed countries, the intentionally planted biomass on agricultural land will play the key role in the mid- and long-term perspective (due to its development potential). Therefore, the study focuses on this type of biomass and does not deal with other types of biomass, such as forest biomass (residues) and residual biomass from agriculture and wood industry.

The proposed methods of energy and economic effectiveness evaluation are illustrated in detail on the case studies of cogeneration (power and heat production) from maize in the biogas station and biomethane production. This detailed analysis is accompanied with the results of analysis for selected cases of biomass production and utilization for energy purposes—biomass from short rotation coppice (SRC) plantations for combined heat and power (CHP), Reed Canary Grass for CHP, wheat and rape seed for liquid biofuels production, and maize for biomethane production.

These case studies represent typical ways of energy biomass production on agricultural land in the Czech Republic and other countries with similar soil and climatic conditions.

Data Sources

The case studies on effective use of biomass in the Czech Republic are mainly based on the following data sources:

- Published data on typical yield curves for individual types of energy crops—Vávrová and Knápek,[12] Havlíčková et al.,[17] Havlíčková et al.,[18] Voříšek et al.[19]
- Statistical data on average yields of agricultural crops—Czech Statistical Office (CZSO).
- Data on typical investment and operational costs of individual transformation technologies for biomass—Voříšek et al.[19]

METHODOLOGY

The evaluation of the use of energy biomass from the system point of view is based on respecting the whole biomass fuel cycle, starting from biomass production (on agricultural land), through energy conversion processes (e.g., transformation of biomass in solid, liquid, or gas biofuel) to use of biomass (or biofuel) for production of different forms of end-use energy.

The systemic view also means that the whole life-cycle of each part of the fuel cycle needs to be correctly evaluated (from economic and energy point of view). For instance, in case of biomass production, one needs to respect all activities related to project preparation, implementation (through the whole life-time) and termination (together with returning agricultural land to its original state).

The comparison of (energy and economic) effectiveness of individual types of biomass is complicated firstly due to different ways of assessing energy efficiency of conversion technologies and secondly due to the place of conversion process, which may in some cases limit the actual use of the final product. For instance, a biogas station (with a gas cogeneration unit) simultaneously produces two products: electricity and heat. Therefore, the two products cannot be assessed separately and their relation is basically given for a given cogeneration unit. To estimate a useful product (effective use of energy by end-users), it is necessary to deduct own technological consumption and any other energy losses.[a]

Biomass Fuel Cycle—From Biomass to the Final Useful Product

To address the aims of the study, the biomass fuel cycle is defined as a set of individual stages from biomass production on agricultural land to the transformation of biomass into the energy products for final energy consumers. The biomass fuel cycle uses agricultural land, energy needed for biomass production and the financial sources to carry out individual stages of fuel cycle (see Figure 1).

The fuel cycle of biomass is determined both by the type of biomass and by the conversion technology and the related type of output. For instance, biomass from energy crops such as Reed Canary Grass can be used for the production of bio-pellets, which are in turn used in CHP. Alternatively, this type of biomass (harvested in spring) can be directly fired to produce electricity and heat again.[18] In the latter case, there is no need for the conversion of biomass into an intermediate product. Similarly, an intermediate product is not needed in case of biomass production from SRC plantations. The plantations are harvested with special harvesting machinery and biomass is gained directly in form of wood chips. Conversely, in case of maize used as the input in the biogas station, the biomass is firstly transformed into biogas (intermediate product), which is then used for the production of a useful product for the end-user—in this case, electricity and heat or biomethane.

The evaluation method of the biomass use effectiveness is based on a simplified assumption that fuel cycles are compared at their output (as to the amount of energy contained in individual useful end-use energy products). It is assumed that the energy content is equivalent disregarding the type of product and its use by end-users is also neglected. For instance, in case of cogeneration, electricity and heat are considered the 'same' useful products—both products are expressed in same units (GJ or kWh, converted by physical equivalent). Furthermore, the method disregards the transport of the product to end-users as the location of end-users may vary; moreover, this aspect is negligible when comparing the effectiveness of biomass produced/gained on agricultural land.

Energy Flows and Losses in Fuel Cycle

Agricultural land and its availability for energy biomass is the main limiting factor. All other inputs in

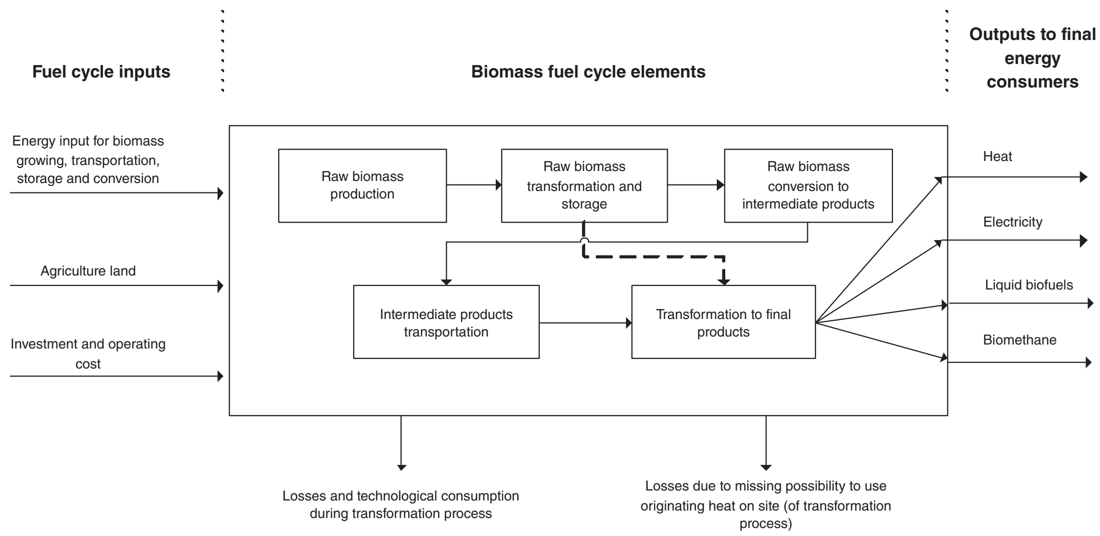

FIGURE 1 | Structure of the biomass fuel cycle.

biomass fuel cycle can be considered as non-limiting factors in the task. In the presented method, (energy) effectiveness of a given biomass fuel cycle is expressed as a ratio of energy produced per unit of agricultural land and energy contained in end-use products (respecting energy consumption in individual parts of the fuel cycle).

The biomass yield on agricultural land depends, among other things, on the soil and climatic conditions in the given location, type of biomass crop, agro-technical processes used, and so on. Based on these parameters, the (brutto) energy yield of biomass per one hectare of land ranges broadly from 50 to 220 GJ/ha.[18] In this study, we use the average, typical values of hectare yields in the climate and soil conditions of the Czech Republic (see Refs 3, 12, and 17–19).

Gross production of energy in biomass (BEG) from one hectare of land for a given kind of energy crop can be expressed as follows:

$$\mathrm{BEG}_i = Y_i \cdot \mathrm{HV}_i \ [\mathrm{GJ/ha}] \tag{1}$$

where BEG_i is the energy gain (gross) of one hectare of land for i-type of biomass [GJ/ha], Y_i is the hectare yield of i-type of biomass [t/ha], and HV_i is the heating value of i-type of biomass (while considering typical parameters of moisture and share of dry matter) [GJ/t].[b]

Energy losses during the biomass transportation and storage are reflected by the coefficient CELts_i:

$$\mathrm{CELts}_i = 1 - \frac{\mathrm{BEGts}_i}{\mathrm{BEG}_i} \ [\mathrm{GJ/GJ}] \tag{2}$$

where BEGts_i is the energy content in i-type of biomass after transportation and the storage [GJ], and CELts_i is the specific energy losses in the biomass transportation and storage [GJ/GJ].

The third stage of the biomass fuel cycle is its conversion to intermediate product (e.g., production of pellets from biomass or production of biogas through anaerobic fermentation). The energy efficiency of biomass transformation (with the use of k-fold conversion technology) to produce intermediate product is expressed by the coefficient $\mathrm{CELcip}_{k,i}$:

$$\mathrm{CELcip}_{k,i} = 1 - \frac{\mathrm{BEGip}_{k,i}}{\mathrm{BEGts}_i} \ [\mathrm{GJ/GJ}] \tag{3}$$

where $\mathrm{BEGip}_{k,i}$ is the energy content in i-type of biomass after conversion into intermediate product using k-conversion technology [GJ], and $\mathrm{CELcip}_{k,i}$ specific energy losses in the biomass conversion into intermediate product [GJ/GJ].

The fourth stage of the fuel cycle is the transport of intermediate product to the place where it is transformed into the end-use (useful) energy product:

$$\mathrm{CELtp}_{k,i} = 1 - \frac{\mathrm{BEGtp}_{k,i}}{\mathrm{BEGip}_{k,i}} \ [\mathrm{GJ/GJ}] \tag{4}$$

where $\mathrm{CELtp}_{k,i}$ is the specific energy losses in the intermediate products transportation (after conversion to intermediate product using k-technology) and storage [GJ/GJ], and $\mathrm{BEGtp}_{k,i}$ is the energy content in i-type of biomass after transportation and storage of intermediate product [GJ].

The fifth stage of the fuel cycle is the transformation of biomass (or the intermediate product) into useful end-use product(s). Efficiency of such transformation is expressed by the coefficient $\mathrm{CELtfp}_{l,k,i}$:

$$\mathrm{CELtfp}_{l,k,i} = 1 - \frac{\sum_{m=1}^{n} \mathrm{ECfp}_{l,k,i,m}}{\mathrm{BEGtp}_{k,i}} \; [GJ/GJ] \qquad (5)$$

where $\mathrm{CELtfp}_{l,k,i}$ is the energy losses in transformation of biomass (or intermediate product) into final products [GJ/GJ], and $\mathrm{ECfp}_{l,k,i,m}$ is the energy content in m-type of end-use product using l-transformation technology (assuming i-type of biomass and k-conversion technology into intermediate product) [GJ].

Useful energy in end-use product is a brutto value, i.e., one that has not been corrected for its own energy consumption for the respective technology (e.g., heat consumption in the fermenter, technological electricity consumption, and other). Simultaneously, in many cases, the whole useful product is not fully effectively utilized, as for instance in cases where it is not possible to fully use all heat produced in CHP in the biogas station or in cogeneration units in general. It is caused by the fact that biogas stations are usually built in lower density areas and the long distances to end-users cause disproportionate increase in costs of the delivered heat leading to its uncompetitiveness (see also footnote ‘a’). The share of heat that cannot be effectively used differs for different technologies. Based on experience from the Czech Republic, we assume that the coefficient of unused heat is significantly lower for direct firing of biomass than it is for biogas stations.[c]

The technology’s own energy consumption is expressed by the coefficient $\mathrm{CESCtfp}_{l,k,i}$ which is defined as the relative share of energy consumption for technological purposes on total amount of energy in end-use products:

$$\mathrm{CESCtfp}_{l,k,i} = \frac{\sum_{m=1}^{p} \mathrm{ESCfp}_{l,k,i,m}}{\sum_{m=1}^{p} \mathrm{ECfp}_{l,k,i,m}} \; [\mathrm{GJ/GJ}] \qquad (6)$$

where $\mathrm{CESCtfp}_{l,k,i}$ is the specific own energy consumption of l-transformation technology [GJ/GJ], and $\mathrm{ESCfp}_{l,k,i,m}$ is the own consumption of m-form of energy (electricity and heat) for technological purposes of l-conversion technology [GJ].

The rate of nonuse of the end-product is expressed by the coefficient $\mathrm{CELnufp}_{l,k,i}$—it is a ratio of nonused energy after conversion on total amount of energy in end-use (useful) energy products potentially deliverable to final consumers.

$$\mathrm{CELnufp}_{l,k,i} = \frac{\sum_{m=1}^{p} \mathrm{ENUfp}_{l,k,i,m}}{\sum_{m=1}^{p} \mathrm{ECfp}_{l,k,i,m}} \; [\mathrm{GJ/GJ}] \qquad (7)$$

where $\mathrm{CELnufp}_{l,k,i}$ is the coefficient of nonuse of the end-product(s) [GJ/GJ], and $\mathrm{ENUfp}_{l,k,i,m}$ is the amount of unused energy in m-type of end-use energy product (with l-transformation technology) [GJ].

With regard to the outputs of the biomass fuel cycle, the energy consumption of all processes can be considered as equivalent to energy losses in transformation processes. However, following the principles of calculation of net outputs of a biomass cycle, one has to differentiate between energy consumption of different processes and losses in transformation processes in different stages of the cycle. Energy consumption of processes in the given fuel cycle is deducted from the total energy contained in end-use (useful) energy products.

As we assess the energy effectiveness of biomass use from a broader, systemic point of view, we have to deduct the energy consumption in the individual stages of the given fuel cycle.

- ECBEG_i: Energy consumption for biomass production (we assume direct energy consumption of biomass production—consumption of fuels for agrotechnical machinery used for plantation establishment, harvest, and short-distance transport from the field). Energy consumption is related to one hectare of agricultural land and is considered fixed for the given type of biomass (some dependency of fuel consumption on biomass yield can be neglected).
- ECts_i: Energy consumption for biomass transport and storage. In many cases, this part of consumption can be neglected because biomass conversion is carried out in the place of biomass production and the transport distances are very short (as in case of biomass used in biogas stations). Energy consumption for storage of biomass can be neglected—biomass is usually stored in open areas (e.g., as packed biomass or chips) or in silage pit or silos (biomass for biogas stations) and therefore energy consumption of storage is minimal.
- $\mathrm{ECcip}_{k,i}$: Energy consumption of biomass conversion to intermediate product, e.g., energy consumption of biomass drying and pelleting or in case of biogas stations heat for heating of the fermenter.

- $ECtp_{k,i}$: Energy consumption of transport and storage of the intermediate product. Typically, this means the energy consumption of biofuels transport to the places of their further use in production of electricity and heat. The consumption may be considered negligible if the intermediate product is used directly in the place of its production.
- $ESCtfp_{l,k,i}$: Own energy consumption of the l-type of equipment/machinery transforming biomass or intermediate product in end-use (useful) energy products.

The total net effect $BEGnetto_{l,k,i}$ (in energy units, GJ or kWh) resulting from production of i-type of biomass on 1 ha of agricultural land assuming utilization of k-technology for the conversion into the intermediate product and l-technology of transformation into the final products is defined as follows:

$$\begin{aligned} BEGnetto_{l,k,i} &= BEG_i \cdot \left(1 - CELts_i\right) \cdot \left(1 - CELcip_{k,i}\right) \\ &\times \left(1 - CELtp_{k,i}\right) \cdot \left(1 - CELtfp_{l,k,i}\right) \cdot \left(1 - CELnufp_{l,k,i}\right) \\ &- ECBEG_i - ECts_i - ECcip_{k,i} - ECtp_{k,i} \\ &- ESCtfp_{l,k,i} \quad [GJ/ha] \end{aligned} \tag{8}$$

Economic Effectiveness of Energy Biomass Use

Individual processes in the given fuel cycle are accompanied with respective costs for their realization. When assessing the effectiveness of different types of biomass grown on agricultural land, it is essential to consider not only the energy efficiency itself, but also the economic effectiveness of the end-use energy products.

When assessing effectiveness of different uses of energy biomass produced on agricultural land, one has to closely respect the following principles (they are basically analogous to requirements for economic assessment of different investment variants) see, e.g., 22[d]:

- Lifetime of the main equipment (plans) has to be respected.
- All costs induced by processes in a given cycle have to be covered.
- Market pricing of all inputs has to be used.
- Adequate rate of return on invested capital has to be respected.

Biomass is valued either through market prices (if it is a generally traded commodity, such as maize for a biogas station) or through economic models simulating given biomass production project if the given type of biomass does not have a market price (due to limited volume of production). In case of the Czech Republic, this applies to SRC plantations or energy crops such as Reed Canary Grass. The economic model is an instrument to determine a so-called minimum price per unit of production (e.g., price of 1 GJ of fuel heat in biomass), which ensures that the producer gains an adequate rate of return on capital invested in the project of biomass production on agricultural land. More information on the application of economic models in estimating the price of intentionally planted biomass can be found, e.g., in Refs 12 and 16.

The authors are aware that a full economic comparison needs to account for opportunity costs of energy biomass (conventional crops).[9] However, such an approach goes beyond the scope of the present study.

Another important input in economic effectiveness evaluation of biomass use is the costs of conversion technologies (for conversion of biomass into intermediate products) and of technologies for biomass (or intermediate products) transformation into final products. As we compare the effectiveness of use of different technologies without knowing the concrete investor or the ways of the project's financing, it is appropriate to use so-called levelized costs. Levelized costs of energy are defined as follows[24]:

$$LCOE_l = \frac{a_{T,l} \cdot CAPEX_l + OPEX_l + FEX_l}{W_l} \quad [EUR/GJ] \tag{9}$$

where $a_{T,l}$ is the annuity factor for given physical lifetime of l-th conversion technology and given rate of return [−], $CAPEX_l$ is the investment cost of l-th conversion technology [EUR], $OPEX_l$ is the annual operation cost of l-th conversion technology [EUR], FEX_l is the annual fuel cost of l-th conversion technology [EUR], and W_l is the annual energy output in final (energy) product using l-th conversion technology[e] [GJ].

In principle, levelized costs are not 'mere' costs, because they entail the rate of return on capital. Annuity factor reflects the volume of adequate rate of return. The formula of levelized cost (Eq. (9)) assumes constant prices and does not calculate with taxation and the way of financing (more on the method of levelized costs e.g., in Ref 25).

Conversely to calculation of 'net energy gains' from the biomass fuel cycle (see Eq. (8) for $BEGnetto_{l,k,i}$ calculation), the calculation of specific costs of energy in the final product does not include the deduction of energy used for biomass production,

TABLE 1 | Input data for energy effectiveness evaluation

Type of biomass and its use	Y_i [t/ha]	HV_i [GJ/t]	$CELts_i$ [GJ/GJ]	$CELcip_{k,i}$ [GJ/GJ]	$CELtfp_{l,k,i}$ [GJ/GJ]	$CESCtfp_{l,k,i}$ [GJ/GJ]	$CELnufp_{l,k,i}$ [GJ/GJ]
Maize (biogas CHP)	40	5.4	0.1	0.33	0.15	0.15	0.35
Wheat (bioetanol production)	5	16	0.01	—	0.49	0.35	0
SRC (direct burning, CHP)	24.4	6.9	0.1	—	0.2	0.05	0.1
Rape seed (FAME production)	3	23.9	0.01	—	0.42	0.45	0
Maize (biomethane production)	40	5.4	0.1	0.33	0.08	0.25	0
Reed Canary Grass (spring harvest, direct burning, CHP)	10	12	0.1	—	0.2	0.05	0.1

Source: yields—Refs 12 and 17–19, efficiencies of conversion technologies, technology's own consumption of energy,[19] data on losses in transportation and storage.[19] Data on losses in transportation and biomass storage were checked against the results of research studies on energy utilization of biomass[26] and own experience of authors.
Note: It is assumed that the intermediate product is directly utilized on the site as the input for the production of end-use products, i.e., the transportation of the intermediate product is neglected.

transportation, and storage (energy in fuels, fertilizers, etc.). The reason is that this 'indirect' consumption (loss) of energy enters the calculation as part of costs of biomass production.

Specific costs of production of one unit of energy $SCPE_{l,i}$ (kWh in final products) from i-type of biomass using l-type of transformation technology are calculated as follows[f]:

$$SCPE_{l,i} = \frac{BP_i \cdot 3.6}{(1 - CELcip_{k,i}) \cdot (1 - CELtfp_{l,k,i}) \times (1 - CESCtfp_{l,k,i} - CELnufp_{l,k,i})} + \frac{a_{T,l} \cdot CAPEX_l + OPEX_l}{LF_k \cdot IPT_k \cdot (1 - CESCtfp_{l,k,i} - CELnufp_{l,k,i})} \times [EUR/kWh] \quad (10)$$

where BP_i is the price of biomass expressed as price of heat in fuel [EUR/GJ], LF_k is the load factor (of total installed capacity in electricity and heat) [h], and IPT_k is the total installed capacity in electricity and heat [kW].

If there is only one output of the conversion technology, the yearly utilization of installed capacity and total installed capacity are related directly to this product. If there are more outputs (e.g., CHP in a biogas station), the above principle, in which energy of both products is summed up, needs to be respected. In case of the biogas station, the yearly utilization of total installed capacity is related to the total installed capacity (in electricity and heat), not only to electricity.

RESULTS

Evaluation of Energy Effectiveness of Energy Biomass

The detailed application of the model is demonstrated on the maize used as the input in the biogas station with the cogeneration unit. Other five examples of biomass fuel cycles are presented in aggregate results. The input data for calculation are summarized in the Table 1.

Energy consumption for transportation has been estimated at 1–2 GJ/ha (average maximum distance of biomass transportation 50 km) and energy consumption for biomass production (incl. harvest) to 8 GJ/ha (wheat and Reed Canary Grass), 15 GJ/ha (rape seed and maize) and 20 GJ/ha (SRC).[19] The detailed overview of energy flows for maize and CHP in biogas station is shown in Figure 2.

As shown on Figure 2, the net output is (only) 39.5 GJ/ha (from 216 GJ/ha of the gross energy gain from maize). The output value is influenced namely by:

- biomass yield on agricultural land—depending on the climate and soil conditions in given location, and
- the coefficient of nonutilization of the produced end-use (useful) energy product.

These two coefficients have the highest variability depending on the conditions of biomass production and possibility of utilization of the end-use (useful) energy product by the final energy consumers. All other coefficients of losses and energy consumption have relatively low variability and depend mainly on technology (e.g., energy efficiency of cogeneration unit, energy efficiency of biomass transformation into biogas, energy losses during biomass storage, etc.). The comparison of results for six analyzed biomass fuel cycles are presented in Figure 3.

The results show that the most energy effective way of biomass production and utilization (in terms of net energy gain per one hectare) is the third example

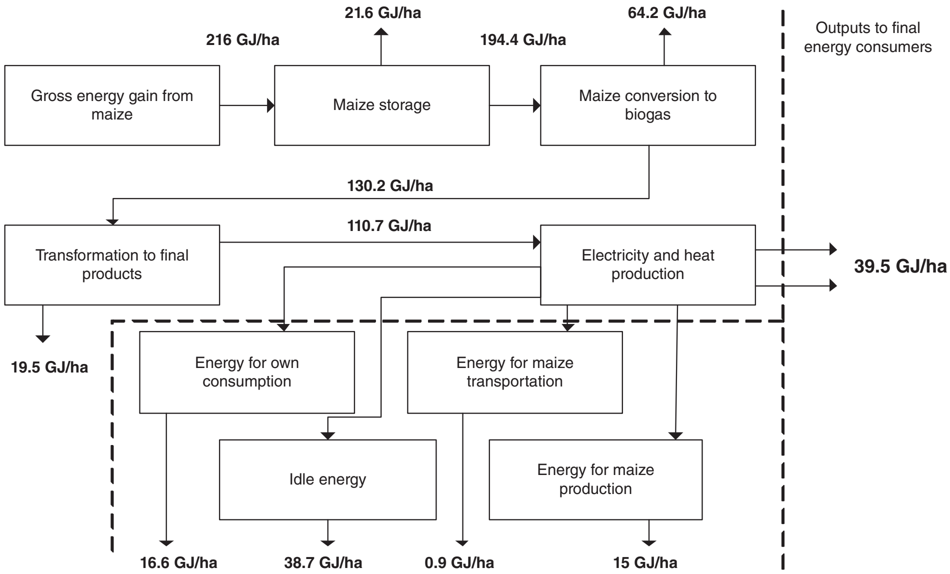

FIGURE 2 | Detailed overview of energy flows of biomass utilization—case example of maize as the input in the biogas station for power and heat production (CHP).

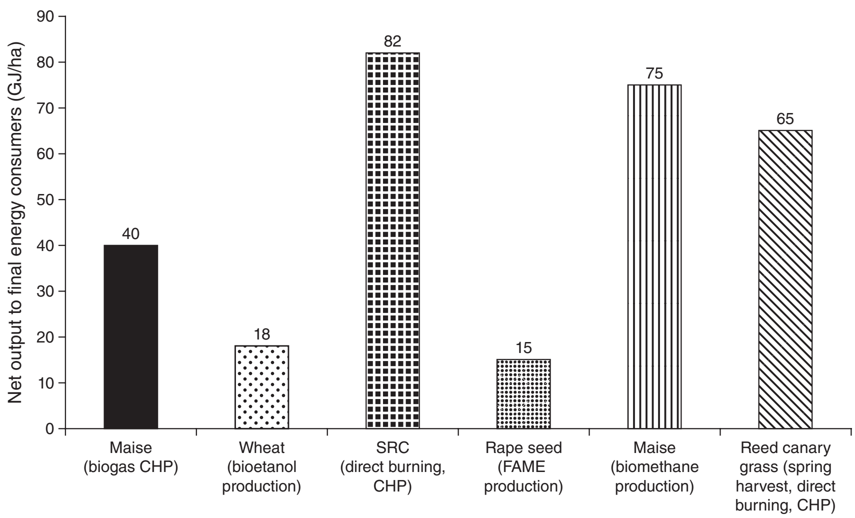

FIGURE 3 | Comparison of net output for individual biomass fuel cycles—case example of the Czech Republic. CHP: combined heat and power.

(SRC for CHP) with net energy gain of 82 GJ/ha of agricultural land, followed by maize for biomethane production.

The energy efficiency of maize used for biogas stations and CHP is strongly influenced by the value of unused (wasted) energy. As was previously discussed, biogas stations are usually located in places where effective utilization of all heat can hardly be attained. In the current Czech conditions, one can assume approximately the 35% share of unused end-use (useful) energy products (i.e., coefficient $CELnufp_{k,l,i} = 0.35$).

Conversely, cogeneration plants using biomass for heat production and delivery are usually located directly in towns and villages, thus offering much better conditions for heat utilization. This means that the coefficient of nonutilization of end-use (useful) energy products (heat) tends to be much lower—in our calculations, we assume maximum 10%.

If the same coefficient was applied to maize and CHP (thanks to higher possibilities to utilize the produced heat, resulting in coefficient $CELnufp_{l,k,i}$ of 0.1), the net output from the cycle for maize and CHP would increase from 40 to 67 GJ/ha and would be closer to the energy efficiency of the maize for biomethane cycle.

Evaluation of Economic Effectiveness of Energy Biomass—Maize Production for the Biomethane

Similarly to the evaluation of energy effectiveness, the principle of calculation of economic effectiveness is demonstrated on the example of biomass (maize) production for biomethane, using typical values of costs in the Czech Republic.

The costs of the preceding stages of the fuel cycle are reflected in the biomass price at the entry to the plant (as we assume the market price of biomass input). We use the same values of coefficients $CESCtfp_{l,k,i}$ and $CELnufp_{l,k,i}$ as in the calculation of energy efficiency. The specific investment cost and load factor (utilization of installed capacity in power and heat) are estimated at 2500 EUR/kW[g] and 7800 h, respectively.[h] Fuel costs (derived from the typical cost of maize silage) are estimated at 5.9 EUR/GJ (of input biomass). Other annual operational costs (maintenance, power consumption, manipulation with the silage, labor costs, etc.) are estimated at 8.5% of capital investment.[i] The annuity factor a_T is calculated using the discount rate of 7% and 20 years of technology lifetime.[j] The fuel costs at the entry to the plant are 6.56 EUR/GJ (assuming 10% of losses in the silage storage).

The specific costs $SCPE_{l,i}$ consist of two components that can be calculated separately—see Eq. (10). The first part of Eq. (10) represents the fuel costs transformed to the final product. The second part of Eq. (10) reflects the costs of conversion technology. If we calculate with unitary power IPT_k, then the investment costs $CAPEX_i$ and other operational costs $OPEX_i$ are also related to a unit of energy.

Using the above mentioned values, we get Eq. (10) in the following form:

$$SCPE_{k,i} = \frac{6.56 \cdot 3.6}{(1-0.33)\cdot(1-0.08)\cdot(1-0.25-0)} + \frac{0.0944 \cdot 2500 + 2500 \cdot 0.085}{7800 \cdot 1 \cdot (1-0.25-0)} \cdot 1000 = 51.1 + 40.3 + 36.3 = 127.7 \times [\text{EUR/MWh}] \quad (11)$$

Total specific costs of biomethane production equal to 127.7 EUR/MWh, consisting of 51.1 EUR/MWh of fuel costs, 40.3 EUR/MWh of the fixed costs from the investment, and 36.3 EUR/MWh of the fixed operating costs.

The method, illustrated on the above case example, then makes it possible to compare the end-use product costs taking into account transformation efficiency and the losses during transformation of biomass into end-use products. It can be used for economic evaluation of different ways of biomass utilization for energy purposes to select optimum strategies for further biomass development.

DISCUSSION

The first method presented in the study is aimed at estimation of net energy effect of different types of biomass grown on agricultural land and processed with different technologies using the full cycle approach. Given fuel cycle is determined by the type of biomass, type of conversion technology for the intermediate product (in some cases, biomass is used directly skipping this conversion), and transformation technology used to transform the intermediate product (biomass) into end-use energy products.

The method takes into account both the amount of energy in biomass and energy consumption to produce biomass including all energy losses in the conversion processes from biomass to end-use products for final energy consumers. The method disregards the use of the final product, but does take into account the fact that in some cases the total produced energy cannot be effectively used up—a typical example being the problem with heat utilization from CHP in biogas stations. Due to location of biogas stations, it is usually not possible to use all produced heat and part of the heat that could be effectively used is lost.

The analysis of six selected case examples of biomass fuel cycles (typical and the most important as to use of energy biomass in the Czech Republic and in other countries with similar climatic conditions) has shown that the most energy effective use of agricultural land are plantations of SRC, which are then transformed to wood chips consequently used in CHP generation. If we compare the use of biomass (maize) for heat and power generation in biogas stations with production of biomethane, the conclusion is that energy efficiency of biomethane production is significantly higher.

However, based on the above energy efficiency analysis, it appears questionable whether biogas stations based on intentionally planted biomass are the most suitable alternative for 'energy' exploitation of available agricultural land as the main scarce resource.

At the same time, the results show that when all losses and energy consumptions are included in the calculation, the net energy benefit of 1 ha of agricultural land is low. Therefore, biomass potential, which is usually expressed as brutto value (in the field), should rather be expressed as netto—in connection to final energy consumption. That appears to be the only way to objectively assess the potential contribution of biomass to meet the energy demand in the given area or country.

We therefore argue that Eq. (8) for the net energy gain from one hectare of agricultural land for energy biomass—$BEGnetto_{l,k,i}$—should be used for calculation of energy biomass potentials. Typical example of such task would be the inputs for state energy policy and search for optimum structure of use of agricultural land for energy purposes with respect to energy effectiveness. This in turn helps to effectively reach targets on RES by 2020 as to the Directive 2009/28/EC,[27] which are defined with respect to final use of all forms of energy and therefore with a focus on the highest productivity and effectiveness.

Under standard conditions, final energy products from biomass are still not competitive with classic fossil fuels and nuclear energy (or products made thereof). To reach a certain share of RES (including biomass), the use and development of RES needs to be supported. The costs connected with such support are directly transferred in energy prices, or burden the state budget (or combination of both). The above methods to calculate specific costs of production of final energy products allow assessing economic effectiveness of individual types of biomass and different conversion technologies. The comparison of economic effectiveness is a core input in the formulation of the biomass use strategy and for the effective setting of biomass development support schemes.

Nevertheless, it is important to keep in mind that effectiveness of different biomass fuel cycles (as to their net energy outputs per 1 hectare of agricultural land) is determined by the technologies used and, above all, by climatic and soil conditions for biomass production. Energy consumption and losses in individual stages of the biomass fuel cycles in different countries can be considered as similar (for the same type of biomass). However, significant differences will occur in biomass yields, resulting from different soils and climatic conditions, but also from different agrotechnologies used and different levels of experience with production of different types of energy biomass. At a rough estimate (as to experience from the Czech Republic), variability of hectare yields is about one order higher than variability in costs of technologies. Therefore, the effectiveness of energy biomass use has to be assessed with respect to the type of biomass, conversion technologies, but also different climatic and soil conditions. The results from one area and state are transferable only to the limited extent.

CONCLUSION

Biomass is widely considered to be one of the most significant renewable energy sources in the mid and longer run. However, in many scenarios and strategies, various incomparable values of its potential share on agricultural land and related costs occur. This is caused, among other things, by the fact that biomass is considered to be rather homogenous category and the specific fuel cycles (including all efficiencies and cost characteristics) are not partly or fully respected. In many cases, the energy inputs in biomass production, transportation and/or conversion into intermediate products are not taken into account. Similarly, in many cases, losses in biomass storage and losses resulting from ineffective utilization of part of originating energy products are neglected.

The method presented in this study allows evaluating the net energy gains from use of agricultural land for energy biomass production, comparing different types of biomass and different types of technologies used to produce final energy products.

When making decisions on the strategies of energy biomass production on agricultural land, not only energy but also the economic effectiveness of production of final energy products need to be respected, as well as the whole biomass fuel cycle. The main principle of the method of specific costs of production is the reflection of all costs of the fuel cycle in the final product(s) delivered to final consumers. This makes it possible to model economic effectiveness of different ways of production and use of biomass and can serve as an effective tool for the formulation of strategic policies in this area.

NOTES

[a] Such losses may stem from a fact that some portion of the ‘netto’ heat cannot be used up in the place of production, as there is no economic demand, and therefore the heat is basically lost; whereas all ‘netto’ electricity can be supplied in the distribution system. Similar problems with heat use are encountered also in other technologies based on firing or conversion processes.

[b] Note: Formulas are based on the following logic of indexes: *i*: i-type of biomass produced on agriculture land (e.g. maize, wooden chips from SRC plantations, wheat, etc.); *k*: *k*-conversion technology used to transform biomass into intermediate product; *l*: *l*-transformation technology of biomass or intermediate products into end-use products; *m*: *m*-type of end-use products.
[c] See method used by the Czech Energy regulatory office for setting of feed-in-tariffs for biomass—Refs 20, 21.
[d] Presented methodology for assessing the effectiveness of different uses of energy biomass produced on agriculture land is based on internal cost occurring in individual parts of given biomass fuel chain. Internal cost, according to their definition, are cost occurring during the economic transactions as the real payments (e.g. rent of land, payments for services, purchase of seeds, etc.) or cost having the meaning of the opportunity cost (here as the time value of money reflected in the value of annuity factor). Different biomass fuel chains significantly differ in their environmental effects, e.g., SRC plantations contribute to increase of biodiversity, high maize penetration can result in problems with soil erosion, etc. Different environmental effects can be included into economic effectiveness valuation through concept of externalities and their internalization. Methodology enables, in principle, inclusion of positive and negative effects related with individual parts of given biomass fuel chains in the form of internalized external cost—this would result in inclusion of new parameter in nominator of Eq. 9. Inclusion of this new parameter would result in expression of levelized cost of energy from social or society points of view and this could serve as the source for strategic decision making—e.g. for the prioritization of biomass fuel chains for state support. However the internalization of externalities is highly difficult and complex process where different calculation methodologies can be used.[23] Therefore, information on internalized cost is not usually available.
[e] Following the above method, when there is more than one product (typically combined heat and power generation), the end-use products are considered as equivalent and *Wl* is calculated as a sum of energy in all end-use products.
[f] Note: CAPEX and OPEX relates to the gross output of transformation technology.
[g] Exchange rate used 25 CZK = EUR.
[h] According to our method, we express the installed capacity as the thermal capacity of the output end-use product.
[i] The average operational costs of biogas stations with CHP are approximately 5–6% of investment costs. Costs for biogas stations with biogas upgrade to biomethane are approximately 8.5% of the investment costs—values used by the Czech Regulatory Office for calculation of feed-in tariffs (see Ref 20).
[j] Values used until the year 2012 for feed-in tariff calculation in the Czech Republic by Energy Regulatory Office.

FURTHER READING

Fazio S, Barbanti L, Venturi G. Energy and economic balances of different dedicated energy crops. In: *17th European Biomass Conference & Exhibition [CD-ROM]*, vol 1. Florencie: ETA—Florence; 2009, 299–301.

Králík T, Valentová M, Knápek J, Voříšek M. Effectiveness of biomass development: life-cycle costs analysis. In: *12th IAEE European Energy Conference*, Venice, 9–12 September, 2012.

Kavka M et al. *Selection from Standards for Agriculture Production in the Czech Republic for Year 2008/2009 (in Czech)*. Praha: UZEI; 2008 ISBN 978-80-7271-198-7.

Kavka M et al. *Standards for Production Technologies in Agriculture (in Czech)*. Praha: UZEI; 2006 ISBN: 80-7271-164-4.

REFERENCES

1. Eurostat. Brussels: renewable energy statistics for EU; 2013. Available at: http://epp.eurostat.ec.europa.eu/statistics_explained/index.php/Renewable_energy_statistics. (Accessed September 15, 2014).
2. MIT. National action plan of the czech republic for energy from renewable sources. 2010. Ministry of Industry and Trade of the Czech Republic. Available at: http://www.mpo.cz/assets/cz/2012/11/NAP.pdf. (Accessed March 15, 2014).
3. Ministry of Agriculture. National action plan of the czech republic for biomass. 2012. Ministry of Agriculture of the Czech Republic. Available at: http://eagri.cz/public/web/file/179051/APB_final_web.pdf. (Accessed March 15, 2014).

4. Ministry of Industry and Trade of the Czech Republic. Update of state energy policy. 2012. Ministry of Industry and Trade of the Czech Republic. Available at: download.mpo.cz/get/47607/53721/595041/priloha 001.pdf. (Accessed March 15, 2014).
5. Beurskens LWM, Hekkenberg M, Vethman P. Renewable Energy Projections as Published in the NREAPs of the European Member States. Report ECN-E-10-069. Available at: http://www.ecn.nl/nreap. (Accessed November 15, 2013).
6. Carneiro P, Ferreira P. The economic, environmental and strategic value of biomass. *Renew Energy* 2012, 44:17–22.
7. Gasol CM, Brun F, Mosso A, Rieradevall J, Gabarrell X. Economic assessment and comparison of acacia energy crop with annual traditional crops in Southern Europe. *Energy Policy* 2010, 38:592–597.
8. Ericsson K, Rosenqvist H, Nilsson LJ. Energy crop production costs in the EU. *Biomass Bioenergy* 2009, 33:1577–1586.
9. Krasuska E, Rosenqvist H. Economics of energy crops in Poland today and in the future. *Biomass Bioenergy* 2012, 38:23–33.
10. Valentine J, Heaton R, Randerson P, Duller Ch. The economics of short rotation coppice in the UK. In: *16th European Biomass Conference & Exhibition [CD-ROM]*, vol. 1. Florencie: ETA—Florence; 2008, 527–528.
11. Monique Hoogwijk M, Faaij A, de Vries B, Turkenburg W. Exploration of regional and global cost–supply curves of biomass energy from short-rotation crops at abandoned cropland and rest land under four IPCC SRES land-use scenarios. *Biomass Bioenergy* 2009, 33:26–43.
12. Vávrová K, Knápek J. Assessment of Miscanthus cultivation for energy purposes in the Czech Republic. *J Jpn Inst Energy* 2012, 91:485–494.
13. Kamimura K, Kuboyama H, Yamamoto K. Wood biomass supply costs and potential for biomass energy plants in Japan. *Biomass Bioenergy* 2012, 36:107–115.
14. Lundmark R. Cost structure of and competition for forest-based biomass. *Scand J Forest Res* 2006, 21:272–280.
15. Patel C, Lettieri P, Simons SJR, Germanà A. Techno-economic performance analysis of energy production from biomass at different scales in the UK context. *Chem Eng J* 2011, 171:986–996.
16. Carapellucci R. Power generation using dedicated woody crops: thermodynamics and economics of integrated plants. *Renew Energy* 2002, 27: 143–159.
17. Havlíčková K, Weger J, Knápek J. Modelling of biomass prices for bio-energy market in the Czech Republic. *Simul Model Pract Theory* 2011, 19:1946–1956.
18. Havlíčková K, Weger J, Šedivá J, Suchý J, Bureš M, Hána J, Jirásková L, Knápek J, Vašíšek J, Gallo P et al. *Analysis of the Biomass Potential in the Czech Republic (in Czech)*. Průhonice: VÚKOZ; 2010, 498 ISBN 978-80-85116-72-4.
19. Voříšek T, Málek B, Maroušek J. *National Action Plan for Biomass—Energy and Technological Biomass Utilization (in Czech)*. Prague: Study for Ministry of Agriculture, SEVEn; 2011.
20. Knápek J, Vašíček J, Valentová M, Králík T. *Study on Feed-In Tariffs and Green Bonuses of Electricity from Supported Sources (In Czech)*. Praha (Prague): Study of ELECTRA ČVUT FEL for Czech Energy Regulatory Office; 2012.
21. Knápek J, Vašíček J, Valentová M. Possible pitfalls in feed-in tariff support scheme: lessons learnt from PV boom in the Czech Republic. In: *Proceedings of the 6th International Scientific Symposium on Electrical Power Engineering*. Košice: Technická univerzita v Košiciach; 2011, 384–387.
22. Brealey R, Myers R. *Principles of Corporate Finance*. Columbus, OH: McGraw-Hill Higher Education; 2003 ISBN 0072467665.
23. Tisdell C. Policy choices about agricultural externalities and sustainability: diverse approaches, options and issues, Working Papers on Economics, Ecology and the Environment, The University of Queensland; 2007.
24. National Renewable Energy Laboratory. Levelized cost of energy calculator. Available at: http://www.nrel.gov/analysis/tech_lcoe.html. (Accessed November 3, 2014).
25. IEA. *Projected Costs of Generating Electricity*. Paris: OECD; 2010.
26. Havlíčková K, Weger J, Benetka V, Knápek J, Kajan M, Moudrý J, Boháč J, Strašil Z, Hutla P, Jevič P et al. Non food utilization of biomass. Research Project for Ministry of Education of the Czech republic 2006–2011. Průhonice: VUKOZ, v.v.i.; 2011.
27. European Union. DIRECTIVE 2009/28/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC. *Off J Eur Union* 2009, L140:16–62.

ANNEX 2

'Energy Biomass Competitiveness—Three Different Views on Biomass Price' *(Knápek et al. 2017)*

Energy biomass competitiveness—three different views on biomass price

Jaroslav Knápek,[1*] Kamila Vávrová,[2] Michaela Valentová,[1] Jiří Vašíček[1] and Tomáš Králík[1]

The paper presents an economic model that provides a systemic approach to the evaluation of growing biomass for energy purposes. We argue that to correctly evaluate the potential of energy biomass, it is necessary to look at it from three different, but interconnected perspectives: (1) minimum price for growing biomass for energy purposes, (2) opportunity costs with respect to other uses of the arable land, namely production of conventional crops, and (3) the aspects of substitution of fossil fuels (e.g., coal) for biomass—the analysis of the demand. Our economic model incorporates the three above points of view. Furthermore, on the case study of the Czech Republic, we show the practical implications of the model on assessment of energy biomass in real conditions. The main findings are that to give the farmers the same rate of return as conventional crops, the price of intentionally grown biomass for energy purposes in the Czech Republic would have to be up to almost three times higher than is the adequate minimum price. On the other hand, in order to be competitive as a substitute for coal for local space heating, the price of biomass would have to be close to zero.

How to cite this article:
WIREs Energy Environ 2017, 6:e261. doi: 10.1002/wene.261

INTRODUCTION

Biomass plays an increasingly important role in both the EU and the Czech Republic energy strategies and is expected to play the decisive role in fulfilling EU 2030 goals in renewable energy sources (RESs). Renewable energies currently contribute 25.4% to the total primary energy production in EU28 (2014), where biomass has a decisive contribution of 63.1%.[1] EU goals to 2030 expect further increase of renewable energies production, so that RES would contribute 27% to total final energy consumption.[2] Since sources of residual and waste biomass are quickly depleted, further increase in the exploitation of biomass for energy purposes (as a decisive RES contributor in the Czech Republic) can be guaranteed only by intentionally grown biomass.

In the current academic debate on economics of energy biomass, three main approaches can be recognized. First, various aspects of energy biomass supply chain are thoroughly described, including economic, social, and environmental aspects of growing of biomass for energy purposes.[3] Economic models determining future biomass prices reflect in detail typical processes of a given type of biomass related to growing, harvesting, storage, processing if needed, and other parts of the logistic chain from the biomass producer to the final consumer.[4–6]

Second, the studies compare the economic viability (competitiveness) of biomass for energy purposes with conventional crops, such as wheat. The idea lying behind is that the arable land is a scarce (limited) resource, and farmers decide on which

*Correspondence to: knapek@fel.cvut.cz

[1]Department of Economics, Management and Humanities, Czech Technical University in Prague, Prague, Czech Republic

[2]The Silva Tarouca Research Institute for Landscape and Ornamental Gardening, Department of Phytoenergy and Biodiversity, Průhonice, Czech Republic

Conflict of interest: The authors have declared no conflicts of interest for this article.

purpose it will be used for, taking into account economic criteria (profitability).[7–10] In such studies, the main focus remains on the calculation of energy biomass production costs.[11]

Third, authors analyze the market demand, where biomass (or other RESs) substitutes fossil fuels, such as coal, exploited in power generation and heat production, and in household heating systems.[12,13] Furthermore, the studies focus on the assessment and analysis of RES support schemes.[14–16]

In this article, we state that only by combining the three above-mentioned approaches in one general model, one is able to make informed decisions on the growth in production of biomass for energy purposes, estimate the 'real' biomass contribution to the primary energy sources (PESs) balance, based on its market competitiveness, and formulate the cost-effective support scheme for intentionally grown biomass. The article therefore offers a systemic approach to the economic evaluation of growing biomass for energy purposes. The functioning of our model is demonstrated on a case example of the Czech Republic.

The paper is organized as follows. In the following section, we present the general model for economic evaluation of biomass for energy purposes. In this section, three main factors that influence the farmers in their decision-making are formulated: the actual cost of growing biomass for energy purposes, the profitability of conventional crops, and the price of substituted fuel. Next, results of the case study on the energy biomass cultivation in the Czech Republic are presented, followed by discussion of some implications of the model and its applicability to other European countries. Last, general conclusions are made.

MODEL FOR ECONOMIC EVALUATION OF ENERGY BIOMASS

The General Approach

The model is based on the presumption that farmers as well as biomass consumers make rational decisions. One can assume that primary motivation of any entrepreneurial entity is the obtaining and maximization of the rate of return on investment.[17]

A farmer (or business company) operating on an agricultural land basically chooses between four standard options:

- conventional agricultural production (aimed at food production);
- production of solid biomass for direct combustion in biomass boilers or as an input for solid biofuel production[a];
- production of inputs for liquid biofuel production (e.g., rapeseed); or
- production of inputs for biogas stations (e.g., maize).

Agricultural land is the only limiting factor here—if one hectare is used for energy biomass production, it cannot be used for conventional production and vice versa. In our model, we simplify the decision-making situation only to the decision between solid energy biomass production and conventional production. But, it is a general principle, when a farmer decides between mutually exclusive alternatives of agriculture land utilization.

We suggest a '*decision-making triangle*' approach depicted in Figure 1.

The first two vertices refer to the analysis of biomass supply (i.e., biomass growing). The first vertex of the triangle is formed by the price for growing biomass for energy purposes (hereafter referred to as c_{min}). The price of intentionally grown biomass c_{min} must provide the investor with the required return on invested capital over the project lifetime.

The second vertex of the decision-making triangle is defined as the price of biomass (hereafter referred to as c_{alt}) which ensures the same net economic effect for the farmer as the conventional commodities such as barley, wheat, etc., considering also agriculture subsidies for conventional production.

The first two vertices define the bottom limit for price of energy biomass intentionally grown on agriculture land (c_{bot_lim}):

$$c_{bot\_lim} = \max(c_{min}; c_{alt}), \qquad (1)$$

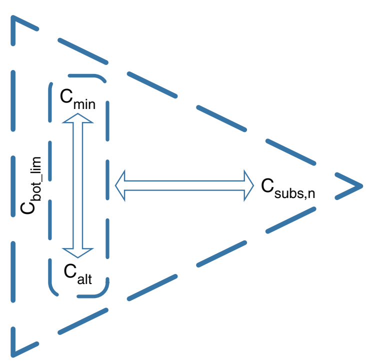

FIGURE 1 | Scheme of the decision-making triangle.

where, c_{min} is the minimum price of grown biomass for energy purposes that assures an adequate rate of return for investors [EUR/GJ] and c_{alt} is the price of grown biomass for energy purposes that assures the same economic benefit as conventional agricultural production [EUR/GJ].

If c_{alt} were higher than c_{min}, one can hardly expect that farmers would be willing to supply biomass for the price c_{min}. Farmers would require at least the price c_{alt}. And, moreover, if we assume that growing of energy biomass is a more risky activity compared to the well-managed and routine planting of conventional production, farmers will require compensations for the higher risk associated with planting of energy biomass. The biomass price would thus be even higher than the price c_{alt}.

Biomass (especially solid biomass) is a direct substitute for conventional fuels—in the Czech Republic, particularly for domestic brown coal. The third possible aspect regarding the biomass price (and the third vertex of the triangle) is consumers' willingness to accept the price of biomass as a substitute for conventional fuels. Consumers will accept (at maximum) such biomass price (c_{subs}) that will assure the same economic effect from the power and/or heat production as it is from the utilization of other (conventional) fuels.

Assuming that the massive development of intentionally grown biomass on agriculture land will not significantly influence the price c_{bot_lim} (the price c_{alt} is independent of possible decreases in biomass production costs), and also assuming that a partial substitution of domestic brown coal for biomass will not significantly influence its prices, then the (upper) limit of the biomass price can be estimated from the prices of substituted fuels and other related costs (such as induced investment costs and changes in operating costs on the side of the power/cogeneration plant operator).

Method for Estimation of Bottom Limit of Biomass Price

The bottom limit of biomass price, as discussed above, is defined as the maximum of c_{min} and c_{alt} prices.

The minimum price of biomass c_{min} is derived from the analysis of economic effectiveness of intentionally grown biomass on agriculture land. To determine the minimum price, economic models are used that reflect all the processes needed for growth of the given energy crop. The economic model must also reflect the entire project lifetime, i.e., the preparation of the project, stand establishment, maintaining, and harvesting, up to the final stand destruction and restitution of the land into its original form. All the processes included in the model are evaluated by market prices for the project inputs—human labor, land rent, fertilizers, services, and so on. The economic model for the given energy crop thus reflects the typical conditions for its cultivation, including yield curves (i.e., the amount of harvested biomass per hectare and year). The model has been fully described in Refs (18–21).

Such economic model for the given energy crop enables simulating the project cash flows for each year of its implementation. Basic criterion for assessing the economic efficiency of the projects is the criterion of net present value (NPV).[17] Minimum price c_{min} is calculated from the condition NPV = 0. In this case, the investor realizes the rate of return equal to discount rate used in NPV calculation.

Determining the value of c_{alt} is more complicated. The reason is that the cultivation of conventional, typically annual, agriculture crops, is compared with energy crops that are often perennial (e.g., short rotation coppices, SRCs). Biomass price c_{alt} represents the price of energy biomass, from which the farmer will have the same benefit as from the conventional crop cultivation. The problem lies in the definition of the 'identical economic return,' i.e., we compare the crops (an entrepreneurial activity, too) fundamentally differing by the length of their cycle. In case of perennial energy crops, (e.g., reed canary grass), the assumed lifetime of the stand is about 10 years, while in case of SRC, the lifetime can reach even 20–25 years. In case of perennial crops, the economic benefit can be interpreted as the return on invested capital to the project preparation and initial expenses on the stand or plantation establishment. The biomass project has then the same character as classical investment projects; i.e., first there are initial investment costs, which further generate the project cash flows.

Conventional crops have typically an annual production cycle, and no significant initial expenses. Actually, the farmers' finances are blocked in the period between the stand establishment and subsequent harvest. A currently used indicator for expressing conventional crop cultivation economy is the profitability calculated as the margin (the difference between revenues and expenses) to the costs on the production of a given crop. This indicator, even though expressed as percentage, cannot be directly compared to the percentage of the return on invested capital, which is used in calculating the minimum biomass price c_{min}.

When comparing the projects of different lifetimes, it is necessary to ensure proper comparability.[22] When comparing, for example, SRC having 20-year lifetime with conventional agriculture annual crops, we can achieve the comparability, e.g., by cultivating annual crop repeatedly so many times until we achieve the identical time with that of SRC. Then, the price of biomass c_{alt} can be determined by a general formula, expressing the balance of net cash flows generated from the energy biomass production (Eq. (2), left side) and net cash flows from the conventional crop cultivation (Eq. (2), right side) per an area unit and the lifetime of the stand/plantation producing energy biomass:

$$\sum_{t=1}^{T_{lf}} \left(c_{\text{alt},t} \cdot Q_t + S_t - E_t\right) \cdot (1 + r_d)^{-t} = \sum_{t=1}^{T_{lf}} (R_t - C_t) \cdot (1 - d) \cdot (1 + r_1)^{-t}, \qquad (2)$$

where, Q_t is the biomass production measured by (lower) calorific value in year t [GJ]; S_t is the subsidies for the biomass cultivation project in year t [EUR]; E_t is the project expenditures on biomass cultivation in year t, including taxes and financing [EUR]; R_t is the revenues from conventional crop cultivation [EUR]; C_t is the cost of conventional crop cultivation in year t [EUR]; i is the average annual inflation [–]; d is the income tax rate [–]; r_d is the nominal discount rate (required return from long-term cultivation activities) [–]; T_{lf} is the lifetime of the project for energy crop (comparative period) [years]; and r_1 is the required return of recurring annual cultivation activities [–].

Note: Equation (2) assumes the same land area used for energy and for conventional crop. We assume that all the agro-technical operations are purchased services, thus in this case, the meaning of variable C_t is identical to expenditures.

The required return in the Eq. (2) is used for discounting of future cash flows to the present value. The discount rate is dependent on the risk rate, which is expressed in the capital asset pricing model (CAPM) as systematic market risk, to which the company has to adapt, because it is undiversifiable.[17] In contrast, specific, unsystematic risk is connected with the functioning of an individual enterprise and is referred to as operational and financial risk that can be diversified.

Expected rate of return has basically three components: risk free rate of return, expected inflation, and risk premium. Real rate of return (which is risk free rate of return plus risk premium) is a very important variable from long-term perspectives. In Eq. (2), on the left side the project with long-term investments is depicted that can be compared, e.g., to the rate of return on long-term bonds. In contrast, on the right side of the equation are presented the discounted cash flows of short-term, annually repeated, projects. It can be illustrated, e.g., as short-term treasury bill investments, repeatedly purchased and held for the same period. Investors prefer an increase in risk premiums to long-term bonds.[17] Moreover, a specific numerical value of the risk premium, i.e., 1.5%, derived from the values monitored over the last century is presented.[17] The calculation of the minimum/alternative price according to Eq. (2) should reflect the difference in a numerical form.

Generally formulated Eq. (2) represents the balance between the present value of the incomes from the cultivation of intentionally planted energy biomass, and the present value of revenues from the conventional agricultural production, per correctly determined comparative period, covering the entire period of the project implementation. In case of a 20-year SRC lifetime and its comparison with the annual crop cultivation, the evaluation period will be set to 20 years.

A long period of time does not enable us to anticipate constant, unchangeable cash flow items. Therefore, in the long run, it is necessary to respect expected inflation.

In Eq. (2), variable $c_{\text{alt},t}$ can be expressed by Eq. (3) that reflects inflation price trends of c_{alt} in time:

$$c_{\text{alt},t} = c_{\text{alt},1} \cdot (1 + i)^{(t-1)}, \qquad (3)$$

and likewise, E_t by Eq. (4):

$$E_t = E_1 \cdot (1 + i)^{(t-1)}. \qquad (4)$$

Eq. (2) is similarly applied also to parameters R_t and C_t. The price in the first year is calculated so as to maintain the balance between the left and right sides of Eq. (2). The price is then interpreted as marginal price, counted since the time when the farmer is willing to consider a transition from the annual conventional crop to the perennial energy crop cultivation.

Price $c_{\text{alt},1}$, can be interpreted as the price of energy biomass from the crops cultivated on the farmland that provides the same economic benefit to the farmer managing the land. It is the price in the first year of the project; in subsequent years (during the project implementation, considering also the stand or plantations), it is increased by expected average inflation rate—see Eq. (3).

In case that the annual energy crops (e.g., triticale) are used for growing energy biomass, the price c_{alt} can be determined a lot easier. We compare the amount of finances generated (on average) from the conventional crop cultivation (Eq. 5, right side) and the amount of finances generated from the energy biomass production (Eq. 5, left side). It is then a simple solution to the equation with respect to the unknown c_{alt}.

$$c_{alt} \cdot Q - E + S = R - C. \quad (5)$$

Minimum price c_{min} varies with individual energy crops, and, in some cases, quite substantially. Moreover, the minimum price of the same energy crops will vary according to the conditions of a land, on which the crop is grown. The habitat conditions influence primarily the amount of biomass production. Thus, we cannot determine one value of c_{min}, but it is necessary to calculate with a range of its values for typical growing conditions and typical energy crops. The calculation of price c_{alt} is based on the calculation of the economic effect from the conventional crops production.

Method for Estimation of the Upper Limit for Future Biomass Price

Biomass, or solid fuels produced from it (briquettes, pellets), is considered a substitute for conventional fuels, especially coal. The upper price limit of biomass (i.e., biofuel) is thus given by the readiness of customers to pay for it. The upper price limit is derived from market prices of substituted fuels with respect to the costs associated with the change of fuel.

Changing fuel (switching to biomass) in practice also brings about other effects, such as lower amount of produced solid waste, reducing local emissions, enhanced comfort, and so on. These effects are not included in the analysis, although in practice they could lead to the acceptance of biomass prices that are higher than those obtained by a direct comparison of the costs per 1 GJ of (lower) calorific value.

The type of a customer plays a major role in assessing the economic aspects in the substitution of conventional fossil fuels (coal) for biomass. The task can be simplified to two types of customers: (1) households using fuel for local space heating, (2) cogeneration plants, or power stations using fuel for generating electricity and/or heat supplied to the centralized heating system. Therefore, setting the upper limit of biomass price is then divided into two separate tasks. First, in case of large power plants, it is usually possible to directly use the baled biomass (with nonwoody energy crops or residual straw from conventional agriculture), or wood chips from SRC plantations. Second, in case of households, such practice is not possible and biomass must be converted into a suitable form—pellets or briquettes. Biomass price is thus increased by the costs of the conversion.

Consumers' decision-making on the amount of money they are ready to invest in biomass or biofuels is influenced also by the additional induced costs. The substitution of one type of fuel for another does not only mean the change in specific fuel costs (price of 1 GJ of lower calorific value), but also the change in technology—e.g., the purchase of a new boiler, changes both in storage and transportation of fuel into the boiler. A rational decision-maker chooses such an option (either to use currently used fuel or, newly, to convert into biomass) that guarantees the maximum economic benefit for the specified evaluation period.

From this perspective, in the case of households, two possible situations can occur. The first case is that the decision-maker wants to renovate the equipment and decides between the currently used technology renovation and switching to biomass. In case of households and local space heating, the cost of technologies can be comparable (assuming substitution of coal with biomass).[23] Then, the upper price limit of biomass (biofuel) is defined by the price of substituted fuel, and is not affected by the costs of changes in technological equipment.

An analogous situation is in the case of power stations and district heating plants. Here, however, the calculation of the biomass price upper limit is influenced by other factors, such as saved emission allowances and support for power (or heat) generation from renewable sources—biomass. In the Czech Republic, significant amounts of electricity (or heat) is produced by using technology called cofiring, where biomass is added to coal in the range of about 5–20%. This technology does not require any further significant investment costs on the biomass utilization, disregarding relatively low costs associated with the biomass logistics.

Upper Limit of Biomass Price from the Perspective of Households (Local Space Heating)

The upper limit of biomass prices for households (local space heating) will be derived for the case, when the household decides on the renovation of the existing technological heating equipment, with the perspective that the cost of modern coal boilers is comparable to the cost of the installation of pellets/briquettes boilers. Crucial role in the decision-making plays the cost of coal (EUR/GJ of lower calorific value), including the transportation costs and the costs on biomass pelletizing/ briquetting, together with biomass transportation costs. The aim is to set up a price upper limit that would be comparable to c_{min} and c_{alt} prices derived from the analysis above.

The upper price limit of intentionally grown biomass, applied in local space heating, can be determined according to the Eq. (6):

$$c_{subs,sh} = SPC_{sh} - C_{conv} - C_{biom,log}, \quad (6)$$

where, $c_{subs,sh}$ is the upper price limit of biomass for local space heating [EUR/GJ]; SPC_{sh} is the specific price of coal (suitable for local space heating), excluding transportation costs [EUR/GJ]; C_{conv} is the specific costs of conversion into pellets/briquettes [EUR/GJ]; and $C_{biom,log}$ is the specific costs on biomass logistics [EUR/GJ].

The costs of the coal and biomass transportation from the producer to the end consumer are considered the same, and therefore they are not included in the calculation. The parameter $C_{biom,log}$ takes into account specific nature of biomass as a biological material, i.e., the energy content losses due to biomass storage during the harvest (biodegradation), including both the losses during the process of conversion into solid biofuels and the storage costs. The cost of pelletizing/briquetting includes also the return on invested capital. The parameter C_{conv} is in principle derived from the methodology of a minimum price.

Upper Limit of Biomass Price from the Perspective of a Power Generating Company

In the EU, the use of biomass as a renewable source of electricity (and/or heat) is generally supported by the respective national RES support scheme. The Czech Republic benefits from the support scheme based on the feed-in tariff (FIT) or feed-in premium (FIP). The logic of both types of support is usually built on guaranteeing the (regulated) return on investment. The upper biomass price limit from the perspective of a power generating company or heating plant can be derived by means of FIP/FIT values for biomass combustion. In many countries, the amount of FIP/ FIT is differentiated according to the type of energy biomass.[24] Intentionally grown biomass has usually higher FIP/ FIT values due to the higher costs of its acquisition.

Using the FIP value for intentionally grown biomass in the following Eq. (7), it is possible to determine:

$$c_{subs,pg} = SPC_{pg} + FIP_{GJ} - C_{biom,log}, \quad (7)$$

where, $c_{subs,pg}$ is the upper price limit of biomass used for power generation [EUR/GJ]; SPC_{pg} is the price of coal used in power plants [EUR/GJ]; and FIP_{GJ} is the feed-in premium value for burning intentionally planted biomass converted into 1 GJ of lower calorific value [EUR/GJ].

The FIP_{GJ} parameter value is calculated from the FIP value (for intentionally grown biomass) and average specific heat consumption in a fuel for power generation.

$$FIP_{GJ} = \frac{FIP}{EF_{av}}, \quad (8)$$

where, FIP is the feed-in premium value for power generation using intentionally planted biomass [EUR/MWh] and EF_{av} is the average efficiency for power generation [GJ/MWh].

As the biomass transportation costs are, as in case of households, considered the same as the costs of coal, they are not included in the calculation.

APPLICATION OF THE ECONOMIC MODEL: CASE STUDY CZECH REPUBLIC

Data sources for Biomass Price Modeling

Conventional Agriculture—Cost, Yields, and Market Price

The data on conventional crops was taken from the official statistics of the Czech Statistical Office and from the surveys carried out by the (Czech) Institute of Agricultural Economics and Information. The data series cover the period from 2008 to 2014. The time span corresponds with the energy biomass growing cycle. It allows accounting for the differences in yields as well as the fluctuations in the commodity markets. The recent available data we can take advantage of is the data from the end of 2014 year. In turn, the data on costs of growing conventional crops is assumed only for the year 2014. The costs of growing crops are relatively stable; the changes can be mainly assigned to the overall inflation rates. Therefore, the averaging is here less meaningful than at yields and market prices.

The following types of conventional crops have been used for the analysis: wheat, barley, maize for grain, and rapeseed. These four types of crops represent almost 70% of total arable land in the Czech Republic, which in 2014 equalled to 2.468 million hectares (see Table 1).

TABLE 1 | Planting Areas of Main Conventional Crop Types, Czech Republic, 2014[25]

	Area [ha]	% of Total Arable Land
Wheat	835,941	34
Barley	350,518	14
Rapeseed	389,298	16
Maize for grain	100,453	4

Table 2 presents the costs of conventional crop production per hectare for the year 2014, average prices of the main crops and average crop yields in the conditions of the Czech Republic for the years 2008–2014.

When calculating economic effectiveness of conventional agricultural production, one has to also add subsidies (i.e., direct payments per hectare of arable land within the Common Agricultural Policy support system—so-called SAPS payments, and the national top-ups). These payments (in total) reached EUR 229/ha in 2014.[29]

Minimum Prices of Energy Crop Intentionally Grown on Agriculture Land

The case study considers four most perspective energy crops for conditions in the Czech Republic, i.e., reed canary grass, schavnat, miscanthus, and SRCs.[19,20] Typical yields of these energy crops in the Czech Republic fluctuate as follows:

- Reed canary grass: 3–6 t (dry matter, DM)/ha, year
- Schavnat: 3–8 t (DM)/ha, year
- Miscanthus: 4–10 t (DM)/ha, year
- SRC: 5.7–11.5 t (DM)/ha, year

At the price level of 2014 (price levels of agro-technical services and land rents in the Czech Republic and the value of SAPS and the national top-ups of EUR 229/ha in 2014), the biomass minimal prices (for a discount of 9%) fluctuate within the following ranges:

Reed canary grass: 5.6–3.1 EUR/GJ
Schavnat: 5.0–2.1 EUR/GJ
Miscanthus: 5.15–2.82 EUR/GJ
SRC: 5.1–2.6 EUR/GJ

Note: Higher minimum price in a price range always refers to a lower biomass yield in the range.

TABLE 2 | Costs of Planting Conventional Crops, Average Prices, and Yields of Conventional Crops, Czech Republic[26–28]

Crop Type	Costs [EUR/ha]	Market Price (EUR/t)	Yield (t/ha)
Wheat	839	165	5.59
Barley	706	166	4.75
Rapeseed	1233	362	3.17
Maize for grain	1048	163	7.95

Note: VAT is not included, 1 EUR = 27 CZK.

Brown Coal

Brown coal (lignite) is not generally traded commodity on international markets. Its price is determined by negotiations between coal and energy companies. At present, the estimated price of coal for electricity production can be about 1.5 EUR/GJ (for more information about brown coal prices in the Czech Republic, see Ref 30).

Specific heat consumption for electricity generation in the Czech modernized brown coal-fired power plants is 10 MJ/kWh (derived from the minimum indicative values defined in Ref 31).

In the Czech Republic, the price of brown coal for households is not regulated and is generally determined by supply and demand. Coal price fluctuates throughout the year; there are also relatively significant regional differences caused mainly by transport distances. The price of brown coal for households (which is suitable for modern coal boilers currently used for individual space heating, at a price level as in 2014–2015) is between 4.93 and 7.15 EUR/GJ (including 21% VAT and excluding transportation), the mean value is then 6.10 EUR/GJ[b].

Costs of Conversion of Biomass into Pellets and Briquettes

These costs are derived from pelleting and briquetting technologies available in the Czech Republic, suitable for local production. The capacity of the production lines is about 1.200–1.500 t of pellets/briquettes per year. Investment costs of pelleting lines are considered to reach EUR 280,000, briquetting lines EUR 380,000. Operating costs of pelleting lines (excluding fuel) are about 62,000 EUR/year, of briquetting lines about 114,000 EUR/year. The costs of pelleting, as in the case of the price of intentionally grown biomass, are derived from a minimum price with a low discount rate (4%), which reflects the assumption of local business operated by the municipality, where the primary goal is not profit, but providing the required amount of pellets/briquettes from locally available biomass.

The data for the calculation of the price of biomass for local energy needs (for households)—$c_{subs,sh}$ has been taken from the project No. TD03000039 supported by the Technology Agency of the Czech Republic on Tools for the analysis of market utilization and competitiveness of biomass for energy needs in local communities, in which the costs of pelleting, storage, and energy biomass losses have been calculated.

Pelleting costs are then ca 4.47 EUR/GJ and briquetting costs 6.69 EUR/GJ. The value of biomass losses during storage and storage costs can be estimated at about 0.20 + 0.15 EUR/GJ.[18,32]

Feed-In Premium Value for Biomass Power Generation

For the year of 2014, FIP values for cofiring intentionally planted biomass with coal were taken from the Energy Regulatory Office price decisions.[33,34] FIP values for 2014 accounted for 54.07 EUR/MWh, and for 2017, the value increased to 90.37 EUR/MWh.

The calculation of c_{subs} price requires a FIP recalculation from the value of EUR/MWh to EUR/GJ of lower calorific value in the used fuel. When using the above-mentioned values of specific heat consumption in fuel for power generation of 10 MJ/kWh, the recalculated FIP value accounts for 5.4 EUR/GJ for 2014.

RESULTS

If the farmer was to achieve the same economic effect in energy crop cultivation as in the cultivation of conventional crops, it would mean a sharp rise in biomass price from the value c_{min} to the value c_{alt}. When considering the same conditions for growing energy crops as at calculation c_{min} and when requesting to achieve a 10-year stand life cycle at reed canary grass, miscanthus and schavnat, or 22 years at short rotation plantation, the price c_{alt} compared with the price c_{min} will be about two to three times higher, depending on the type of crop and the yield curve:

- Schavnat: c_{min}: 2.24–5.19 EUR/GJ, c_{alt}: 4.63–11.44 EUR/GJ
- Reed canary grass: c_{min}: 3.16–5.80, c_{alt}: 8.19–15.85 EUR/GJ
- Miscanthus: c_{min}: 2.82–5.15 EUR/GJ, c_{alt}: 5.19–9.89 EUR/GJ
- Short rotation coppice: c_{min}: 2.74–5.26 EUR/GJ, c_{alt}: 5.56–11.04 EUR/GJ

Using Eq. 6, the biomass price $c_{subs,sh}$ for households (where the biomass in the form of pellets is a substitute for coal) is 0.16 EUR/GJ. The biomass price $c_{subs,pg}$ for coal-fired power plants using cofiring of biomass (formula 7) is 5.55 EUR/GJ.

The results are summed up in the following Figure 2.

The Figure 2 shows that in the current conditions in the Czech Republic, farmers are not likely to switch from conventional crops to energy biomass (c_{alt} in all cases higher than c_{min}). Furthermore, the energy biomass for local needs is not competitive as a

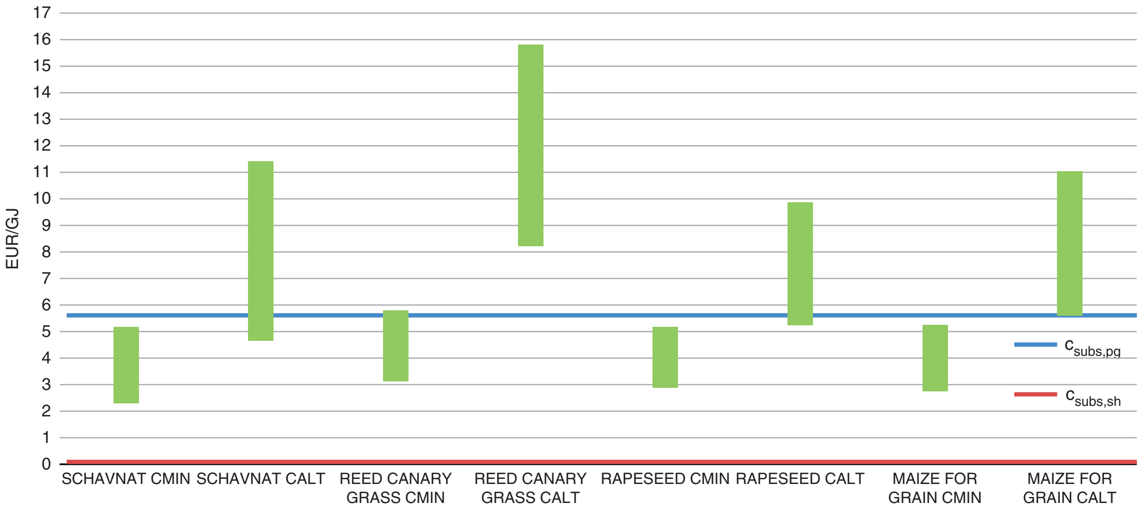

FIGURE 2 | The results of modeling the lower and upper limits of biomass price.

substitute for brown coal. In case of cofiring in large power stations, energy biomass could be competitive (i.e., c_{min} meets $c_{subs,pg}$).

DISCUSSION

A systematic approach to the development of intentionally grown biomass for energy purposes assumes its competitiveness relative to other alternatives, such as natural gas, heat pumps, but, in many countries, coal, as well. What must also be taken into account are opportunity costs, i.e., other options of using agriculture land. Agriculture land is actually the only strictly limited production factor.

The results of the case study presented in the article show that the current high profitability of conventional crops (to some extent, depending on the amount and way of subsidizing this production) causes a significant increase in price of expected supply of intentionally grown biomass from farmers. Price of biomass increases by about 1.8–2.7 times (from c_{min} to c_{alt}), according to the type of energy crops and yield curves. This leads either to noncompetitive biomass prices for the consumers or, conversely, to the fact that farmers are not willing to produce energy biomass.

Economic models used for estimating the future price of intentionally grown biomass from perennial crops usually assume relatively low levels of discount—typically 5–9%.[10,35,36] In the case study of the Czech Republic, the discount value of 8.7% was used for the calculation of c_{min}. It is consistent with the rate of return for power generation from RES in the Czech Republic (the discount rate used to calculate FIT or FIP, using the methodology of minimum price, was about 6–7%). The discount (i.e., 8.7%) covers higher risk connected with energy biomass cultivation.

The costs of establishing perennial crops (typically between 20–35%), harvesting (20–30%), and fertilizers (20–30%) play a key role in determining the minimum price of intentionally grown biomass (besides the biomass yields influenced by climatic and land conditions in the region/country). The costs of land rent also play a relatively significant role in the structure of c_{min} (about 15–20%, depending on the type energy crops).[20,21] Nonwoody energy crops have relatively similar structure; SRC plantations have typically lower costs of fertilization, but higher costs of special harvest (about 40%), when biomass is directly chipped. Conversely, minimally influential are costs of labor force or transportation from the field.

Due to the structure of the minimum price of various types of biomass, the results of calculation of minimum price of energy biomass can be considered transferable to other countries with similar land and climate conditions—typically the Central European countries. Agro-technology prices, based on the prices of machinery, seed and fertilizers, can be considered comparable among individual EU countries. In contrast to the conditions in the Czech Republic, countries such as Germany and Austria have significantly higher prices of land rent, or wage levels. However, this has only a limited impact on the level of minimum price. Given the structure of costs described above, different level of wages can be actually neglected. If the land rent doubles, the minimum price will increase only by about 15–20%. Similarly, increasing the discount from 8.7 to 16% will result in increase of c_{min} by 15 to 30%. Higher growth is evident at SRC plantations, where one-off costs are higher at the beginning of the stand life cycle and the life cycle is about two times higher than that of nonwoody energy crops.

Valuation of energy biomass from the perspective of opportunity costs—i.e., by conventional agricultural production—has four key inputs: (1) (average) level of individual crop production in a given land and climatic conditions, (2) average costs of crop production, (3) level of agricultural subsidies in conventional crop cultivation, and (4) prices of conventional crops. From the perspective of the first and fourth factors, the results of the case study for the Czech Republic can be considered fully transferable to other EU countries with similar climatic conditions (we assume that commodity prices in different countries reflect world prices). The level of agricultural subsidies in the Czech Republic to conventional agriculture is comparable (per unit of land) to Western European countries. The cost of growing crops are slightly lower (especially land rents), but as in the case of energy crops, costs of agrotechnology and fertilizers, which can be considered similar, play a crucial role.

With respect to the above, the relation between c_{min} and c_{alt} for the energy crops, presented in a case study of the Czech Republic, can be considered as a good approximation for other EU countries with similar conditions.

The model intentionally stems from the current situation (current prices, agrotechnologies, biomass and crops yields, etc.) to confront the optimistic assumptions on biomass development with current economic reality. In future, one can expect significant changes in some of the model inputs—among others, changes in absolute level of subsidies of conventional agricultural production (in monetary units per hectare) could occur. Similarly, the overall subsidy scheme could change to incorporate, e.g., requirements for additional measures such as measures aimed at landscape, and biodiversity protection. This could significantly affect the results of the calculation. However, the logic of the model remains unchanged. In contrary, the model could serve to study the potential impact of such changes in subsidy scheme.

Furthermore, the model works with average yields, costs, and processes of conventional agricultural production to demonstrate the general competitiveness of intentionally planted biomass for energy purposes. When analyzing a specific region (e.g., when analyzing the effectiveness of pellets production from locally available residual and intentionally planted biomass), it is necessary to assume the specific local conditions—i.e., to derive biomass yields from soil and climate conditions on the given land plots (as they are the key factors for yields of both conventional and energy crops)[19] and based on that to do the analysis of biomass competitiveness in the given location based on its availability and concrete values of c_{min} and c_{alt} (as the c_{subs} remains stable).

In the Czech Republic, the possibility of substituting coal with local biomass for heating is discussed and supported through various programs (currently, e.g., Green to Savings).[37] However, the problem that needs to be faced is the actual economic accessibility (or competitiveness) of the energy biomass, particularly when considering exploiting locally available biomass reprocessed into pellets or briquettes. The results of the case study for the Czech Republic show that the price of biomass (for achieving a competitive product—e.g., pellets) would have to be close to zero, or even negative.

Under current conditions (fuel prices, the amount of biomass cultivation support, or local pellets production), massive development of the method of energy crop cultivation and the conversion into pellet/briquettes cannot be expected. This economic barrier can be solved in three ways: (1) initiating the restrictions on the use of fossil fuels, especially coal, either by direct limitation of coal availability or by increasing environmental taxes on coal from current low value of 0.31 EUR/GJ of high calorific value, (2) reducing the cost of biomass conversion and logistics and reduction of cost of end-use technology (e.g., pellet boilers), and (3) promoting the exploitation of agriculture land for energy crops (supporting the diversification of farmers' activities, for example, by changing the way in which subsidies are paid) and supporting local production.

The way and the level of support of biomass exploitation play a key role in using intentionally grown biomass for the production of power and/or heat in large power and cogeneration plants. The case study of the Czech Republic reveals that at the current level of FIP for power production from biomass (for cofiring), the price c_{alt} is approaching the price $c_{subs,pg}$ (in some cases, even slightly overlapping). The economic barrier for the exploitation of intentionally grown biomass is substantially lower than in the previous case (biomass as a coal substitute for local heating). However, electricity prices decreasing on stock exchanges cause pressure on the FIP increase, which is evident from the FIP increase between the years 2014 and 2016.[38] Maintaining the amount of FIP would lead to a fast decrease in energy biomass production effectiveness.

The model indicates that the successful development of intentionally grown biomass on agriculture land will happen only if the biomass price derived from the costs of substituted fuel, i.e., the price c_{subs} (i.e., $c_{subs,pg}$ for electricity and $c_{subs,sh}$ for local heating) overlaps or is higher than the price c_{bot_lim} (i.e., higher from the values of c_{min} and c_{alt}). Only then, the farmers have a strong economic incentive for the energy biomass cultivation. The results of the case study for the Czech Republic have shown that in the current conditions such situation is basically not likely to happen

Increase of biomass competitiveness requires changes of the relation between prices c_{subs} (for given type of consumer) and c_{bot_lim}. Price c_{bot_lim} is currently strongly influenced by the subsidy scheme and prices of conventional crops on the market. The competitiveness of biomass utilization (in the form of bio-pellets) by households for local space heating could be significantly increased by the combination of specific measures, such as:

(1) increase of currently low ecological tax imposed on coal (approximately five times to the level 1.5 EUR/GJ),

(2) investment subsidy for pelleting technology to reduce biomass conversion costs (assuming above-mentioned pelleting technology, 100% subsidy would lead to the cost reduction of app. 1.2 EUR/GJ),

(3) investment subsidy for the purchase of pellet boilers to reduce the costs of end-use technology,

(4) additional subsidy per hectare, year for energy crop to reduce the price of raw biomass (i.e., to reduce c_{bot_lim} price). Assuming the logic of c_{bot_lim} price, increase of subsidy for biomass planting (from current value of SAPS and the national top-

ups) would result in further reduction of c_{bot_lim} (as the price c_{alt} would decrease thanks to higher revenues from biomass planting. For instance for reed canary grass increase of subsidy by 50% would result in reduction of c_{bot_lim} price by 1.1–1.6 EUR/GJ).

Combination of all the above-mentioned measures could lead to the reaching of 'break-even point' of biomass competitiveness.

CONCLUSION

Biomass is considered a renewable resource with a great potential for growth in the next few decades in the Czech Republic (and is expected to play decisive role as conditions for the development of utilization of other RESs are limited, especially for photovoltaics).[39] For example, the Czech Energy Policy envisages the doubling of the share of solid biomass consumption on PESs between 2010 and 2040—(from 83 to 160 PJ).[40] This is not possible without the development of a targeted cultivation of biomass on agriculture land. Although, for the next 20–30 years, 800,000–1 million hectares are potentially available for energy crops,[41] we cannot automatically assume their utilization for energy purposes. The situation is similar in other EU countries.

A significant, even major, role in achieving the objectives of the future biomass utilization lies in a proper decision-making of the farmers farming on agriculture land, which is actually the only major limiting factor. The tasks focused on the analysis of the future biomass development often solve the potential of biomass, or its different forms, from the perspectives of production, processing technology, logistics, and so on, and do not take into account all the economic aspects of the task.

We worked out a model combining the analysis of the economics of both biomass growing and alternative agriculture land utilization for conventional production, as well as the analysis of the 'break-even point of biomass price,' when biomass becomes competitive with potentially substituted fossil fuels.

This model enables modeling biomass price from three different perspectives and also enables including the dynamics of the input parameters development (e.g., the expected development of agrotechnologies' effectiveness, fossil fuels market prices, emission allowances prices, etc.). The model enables the combination of different types of businesses with different time constants (e.g., short rotation coppices, SRCs, plantations with up to 25-year lifetime versus annual conventional crop) and different levels of associated risk.

The results of the future biomass price modeling that interconnects all the three different aspects of biomass prices, are important for energy companies in developing business strategies, for farmers making strategic decisions on the land utilization (even with respect to the length of renting agriculture land), and, last but not least, for the policymakers in developing energy policies and proposing cost-effective biomass support schemes. It has been shown that the method is generally applicable, and despite the fact that the case study of the Czech Republic includes specific Czech data, the threat of overestimation of the 'market' biomass potential is relevant to other countries, too.

NOTES

[a] Solid biomass has potentially also material utilization, e.g., the production of fiber boards, and so on. The model for economic evaluation of biomass is also applicable in this case (with changed inputs). However, it is not subject of this paper.

[b] Based on the research of lignite bid prices of brown coal for households, carried out by the authors.

ACKNOWLEDGMENT

The article has been supported by the TAČR (Technology Agency of the Czech Republic, www.tacr.cz), project no. TA04020970. The article also partially uses results of the TAČR project no. TD03000039.

REFERENCES

1. Eurostat. Renewable energy statistics. 2016. Available at: http://ec.europa.eu/eurostat/statistics-explained/index.php/Renewable_energy_statistics. (Accessed January 24, 2017)
2. European Commission. A policy framework for climate and energy in the period from 2020 to 2030. Report No. COM(2014) 15 final, January, 2014. Available at: http://eur-lex.europa.eu/legal-content/EN/

TXT/PDF/?uri=CELEX:52014DC0015&from=EN. (Accessed January 24, 2017).

3. Cambero C, Sowlati T. Assessment and optimization of forest biomass supply chains from economic, social and environmental perspectives—a review of literature. *Renew Sustain Energy Rev* 2014, 36:62–73.
4. Kasmioui OE, Ceulemans R. Financial analysis of the cultivation of short rotation woody crops for bioenergy in Belgium: barriers and opportunities. *Bio Energy Res* 2013, 6:336–350.
5. Fazio S, Barbanti L, Venturi G. Energy and economic balances of different dedicated energy crops. In: *Proceedings of the 17th EU Biomass Conference and Exhibition*, Florence: ETA-Florence. June 29 - July 3, Hamburg, 2009, Available at: http://www.eubce.com/conference/publications-of-papers/proceedings.html
6. van der Hilst F, Dornburg V, Faaij AP., Sanders JP., Ebersen W, Turkenburg W. Economic and energetic performance of energy crops: an analysis for the northern region of the Netherlands. In: *Proceedings of the 16th EU Biomass Conference and Exhibition*, Valencia: June 2-6, 2008 ETA-Florence, 2008, 2585–2590.
7. Sgroi F, Di Trapani AM, Foderà M, Testa R, Tudisca S. Economic assessment of Eucalyptus (spp.) for biomass production as alternative crop in Southern Italy. *Renew Sustain Energy Rev* 2015, 44:614–619.
8. Gasol CM, Brun F, Mosso A, Rieradevall J, Gabarrell X. Economic assessment and comparison of acacia energy crop with annual traditional crops in Southern Europe. *Energy Policy* 2010, 38:592–597.
9. Krasuska E, Rosenqvist H. Economics of energy crops in Poland today and in the future. *Biomass Bioenergy* 2012, 38:23–33.
10. Styles D, Thorne F, Jones MB. Energy crops in Ireland: an economic comparison of willow and Miscanthus production with conventional farming systems. *Biomass Bioenergy* 2008, 32:407–421.
11. Hauk S, Knoke T, Wittkopf S. Economic evaluation of short rotation coppice systems for energy from biomass—a review. *Renew Sustain Energy Rev* 2014, 29:435–448.
12. Nasiri F, Mafakheri F, Adebanjo D, Haghighat F. Modeling and analysis of renewable heat integration into non-domestic buildings—the case of biomass boilers: a whole life asset-supply chain management approach. *Biomass Bioenergy* 2016, 95:244–256.
13. Cansino JM, Pablo-Romero M, del P, Román R, Yñiguez R. Promoting renewable energy sources for heating and cooling in EU-27 countries. *Energy Policy* 2011, 39:3803–3812.
14. Gawel E, Lehmann P, Purkus A, Söderholm P, Witte K. Rationales for technology-specific RES support and their relevance for German policy. *Energy Policy* 2017, 102:16–26.
15. Huber C, Ryan L, Ó Gallachóir B, Resch G, Polaski K, Bazilian M. Economic modelling of price support mechanisms for renewable energy: case study on Ireland. *Energy Policy* 2007, 35:1172–1185.
16. Klessmann C, Nabe C, Burges K. Pros and cons of exposing renewables to electricity market risks—a comparison of the market integration approaches in Germany, Spain, and the UK. *Energy Policy* 2008, 36:3646–3661.
17. Brealey RA, Myers SC. *Principles of Corporate Finance*. New York: McGraw-Hill Higher Education; 2002.
18. Knápek J, Králík T, Valentová M, Voříšek T. Effectiveness of biomass for energy purposes: a fuel cycle approach. *Wiley Interdiscip Rev Energy Environ* 2015, 4:575–586.
19. Vávrová K, Knápek J, Weger J. Modeling of biomass potential from agricultural land for energy utilization using high resolution spatial data with regard to food security scenarios. *Renew Sustain Energy Rev* 2014, 35:436–444.
20. Havlíčková K, Weger J, Knápek J. Modelling of biomass prices for bio-energy market in the Czech Republic. *Simulat Model Pract Theory* 2011, 19:1946–1956.
21. Vavrova K, Knapek J. Economic assessment of Miscanthus cultivation for energy purposes in the Czech Republic. *J Jpn Inst Energy* 2012, 91:485–494.
22. Klíma J. *Optimalizace v energetických soustavách. 1. vyd*. Praha: Academia; 1985. 301 p.
23. TZB-Info. Porovnání nákladů na vytápění TZB-info. 2017. Available at: http://vytapeni.tzb-info.cz/tabulky-a-vypocty/138-porovnani-nakladu-na-vytapeni-tzb-info. (Accessed January 24, 2017).
24. RES LEGAL Europe Comparison Tool. Legal sources on renewable energy. Available at: http://www.res-legal.eu/compare-support-schemes/. (Accessed January 24, 2017).
25. Czech Statistical Office. Areas under Crops Survey—2014. Report No. 270143–14, Prague, July, 2014. Available at: https://www.czso.cz/csu/czso/areas-under-crops-survey-2014-wvlzz3jckc. (Accessed January 24, 2017).
26. Institute of Agricultural Economics and Information. Rentability zemědělských komodit. Prague: Institute of Agricultural Economics and Information, 2016. Available at: http://www.uzei.cz/data/usr_001_cz_soubory/2014.pdf. (Accessed January 24, 2017).
27. Czech Statistical Office. Agricultural producer price indices—December 2015. Prague, January, 2016. Available at: https://www.czso.cz/csu/czso/agricultural-producer-price-indices-december-2015. (Accessed January 24, 2017).
28. Czech Statistical Office. Final harvest figures—2015. Report No. 270141–16, Prague, February, 2016.

Available at: https://www.czso.cz/csu/czso/final-harvest-figures-2015. (Accessed January 24, 2017).

29. Ministry of Agriculture of the Czech Republic. Výroční zpráva přímých plateb 2015. 2016. Available at: http://eagri.cz/public/web/mze/dotace/prime-platby/vyrocni-zprava-pro-prime-platby-za-rok.html. (Accessed January 24, 2017).
30. Bejbl J, Bemš J, Králík T, Starý O, Vastl J. New approach to brown coal pricing using internal rate of return methodology. *Appl Energy* 2014, 133:289–297.
31. Ministry of Industry and Trade of the Czech Republic. VYHLÁŠKA ze dne 5. prosince 2012 o stanovení minimální účinnosti užití energie při výrobě elektřiny a tepelné energie. 441/2012 Col. Available at: http://portal.gov.cz/app/zakony/download?idBiblio=78736&nr=441~2F2012~20Sb.&ft=pdf. (Accessed January 24, 2017).
32. K. Vávrová et al. Model for evaluation of locally available biomass competitiveness for decentralized space heating in villages and small towns, Renewable Energy (2017), http://dx.doi.org/10.1016/j.renene.2017.05.079 (in press).
33. Energy Regulatory Office. Cenové rozhodnutí Energetického regulačního úřadu č. 4/2013 ze dne 27. listopadu 2013, kterým se stanovuje podpora pro podporované zdroje energie. 4/2013 2013. Available at: http://www.eru.cz/cs/-/cenove-rozhodnuti-c-4-2013. (Accessed January 24, 2017).
34. Energy Regulatory Office. Cenové rozhodnutí Energetického regulačního úřadu č. 11/2016 ze dne 22. prosince 2016, kterým se mění cenové rozhodnutí ERÚ č. 5/2016, kterým se stanovuje podpora pro podporované zdroje energie, ve znění cenového rozhodnutí ERÚ č. 9/2016. 2016. Available at: http://www.eru.cz/cs/-/cenove-rozhodnuti-c-11-20-1. (Accessed January 24, 2017).
35. Rosenqvist H, Dawson M. Economics of willow growing in Northern Ireland. *Biomass Bioenergy* 2005, 28:7–14.
36. Olsson R. Production methods and costs for reed canary grass as an energy crop. In: *Bioenergy Research Programme, Publication 2*. Finland, September 14-15, 1993.
37. Nová Zelená úsporám. Available at: http://www.novazelenausporam.cz/. (Accessed January 24, 2017).
38. Knápek J, Haas R. New challenges in RES support. In: *2016 2nd International Conference on Intelligent Green Building and Smart Grid (IGBSG)*. Prague, June 27-29, 2016, 1–4.
39. Sokol R, Bemš J, Starý O. Impact of Solar Energy Boom on Elelctricity Prices. In: Kolcun, M., Kolcumova, I., Kurimsky, J., eds. Proceedings of the 6th International Scientific Symposium on Electrical Power Engineering. 6th International Scientific Symposium on Electrical Power Engineering. Stará Lesná, September 21-23, 2011. p. 380-383.
40. Ministry of Industry and Trade of the Czech Republic. State energy policy of the Czech Republic. Prague, 2014. Available at: http://www.mpo.cz/assets/dokumenty/52841/60946/636123/priloha001.pdf. (Accessed January 24, 2017).
41. Ministry of Agriculture of the Czech Republic. Akční plán pro biomasu v ČR na období 2012–2020. Report No. 97843/2012-MZE-17253, 2012. Available at: http://eagri.cz/public/web/file/179051/APB_final_web.pdf. (Accessed January 24, 2017).

ANNEX 3

'LED Projects and Economic Test Cases in Europe' *(Valentová, Quicheron, and Bertoldi 2015)*

International Journal of Green Energy (2015) **12**, 843–851
Copyright © Taylor & Francis Group, LLC
ISSN: 1543-5075 print / 1543-5083 online
DOI: 10.1080/15435075.2014.887568

Taylor & Francis
Taylor & Francis Group

LED Projects and Economic Test Cases in Europe

MICHAELA VALENTOVÁ[1], MICHEL QUICHERON[2], and PAOLO BERTOLDI[2]

[1]*Czech Technical University in Prague, Praha, Czech Republic*
[2]*European Commission, DG Joint Research Centre, Institute for Energy and Transport, Renewable Energy & Energy Efficiency Unit, Ispra, Italy*

Solid-State Lighting (SSL) is a fast evolving, promising energy-efficient technology, offering a wide range of potential uses. The article presents the status of the existing light emitting diode (LED) pilot actions in Europe, analyzing 106 LED test cases from 17 European countries. Projects from the public and commercial sectors form the focus of this article, with special attention devoted to the economics of LED projects – particularly in terms of energy savings. The results of the test cases demonstrate wide variation. Installations offer energy savings of 59% on average (savings range from 10% to more than 90%). In many applications, LEDs are competitive (with payback time ranging from two to 10 years), yet a large number of projects are still in the trial phase. From the test cases reviewed, the most successful applications are, in terms of savings and economic considerations, replacement of both (1) incandescent light bulbs in traffic light systems, and (2) halogen spotlights in indoor applications. The LED projects bring many co-benefits, including lower maintenance costs, improved lighting characteristics, or improved ambience. Some challenges remain to be addressed, such as to improve the quality characteristics of LEDs and the quality of information and data provided by manufacturers/suppliers, and optimality of LED technology for existing street lighting systems.

Keywords: Light emitting diodes (LEDs), Energy-efficient lighting, Solid-state lighting (SSL), Public sector, Commercial sector

Introduction

The first commercialized Light Emitting Diodes (LEDs) were developed several decades ago (Dupuis and Krames 2008). However, practical test cases for high-brightness (HB) white-light LEDs became more common only in the last five years or so. In spite of this rather short history, LEDs are being used more and more in different lighting installations. Solid State Lighting (SSL – hereafter generally referred to as LEDs) is perceived to be the most innovative technology emerging in the market (e.g., Bertoldi and Atanasiu 2008; European Commission 2011c). The European Commission is focusing on SSL and has published a Green paper on SSL "Lighting the Future: Accelerating the Deployment of Innovative Lighting Technologies" (European Commission 2011c), proposing new policy initiatives to promote this technology.

Given the relative novelty of the technology, the current debate on LEDs focuses on their optical and technical characteristics, often compared with other light sources, and on monitoring of these characteristics over time (e.g., Khan and Abas 2011; Ryckaert et al. 2012). Even though LEDs are seen as the light of future (Richards and Carter 2009), some cautiousness remains and it is foreseen that LEDs will take over only gradually (Dubois and Blomsterberg 2011).[1] In addition, the performance in terms of quantity and quality of light will vary a lot from one LED installation to another. The comparison with other light sources is therefore complex.

Practical case studies are not much available and focus mainly on specific uses and characteristics of LEDs as part of independent energy (lighting) systems (e.g., Adkins 2010; Huang et al. 2010; Pode 2010). Yet, an overview of the current state of the art in LED applications and practical uses has been developed a little.

The aim of this article is to present the status of the existing LED pilot actions in Europe. Specific attention is given to the economics of LED projects with a focus on energy efficiency. Although a generalization of different test cases is not possible, this article highlights and assesses the main features and experiences from LED test cases and illustrates them on selected pilot projects.

Light emitting diodes nowadays offer a wide range of potential uses (varying from traffic lights to elevator lights and showcase lights to bed lamps). This article provides an overview of LED projects. The scope of the overview was limited to test cases in Europe and was carried out in 2011. Even though the overview is not exhaustive, the article provides a representative selection of the most relevant test cases to give as broad a picture as

Address correspondence to Michaela Valentová, Czech Technical University in Prague, Technická 2, 166 27 Praha 6, Czech Republic. E-mail: michaela.valentova@fel.cvut.cz
Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/ljge.

[1]For more information on other energy efficient lighting technologies that are not analyzed in the article, see, for instance, Yang and Hsiao (2006) for high-pressure sodium lamps, or Teng (2013) for fluorescent lamps.

possible of what has been currently going on in Europe in LED installations. Special attention is given to the economics of LED projects.[2]

The article begins with an analysis of the types of installations in which LEDs are used. The main features of the projects are highlighted. It is followed by the analysis of savings (in monetary and technical units) and discussions about the economics of the installations. The last two sections are dedicated to the main advantages and benefits and drawbacks of the projects, as perceived by the stakeholders.

The projects come mostly from the tertiary and public sectors, but also from the industry.

Methods and Limitations

The analysis of LED projects is based on a survey, carried out from mid-June to the end of August 2011. Lighting experts from different sectors were asked to provide references and details on LED pilot projects across Europe. A method of snowball sampling, in which the existing acquaintances provide references and contacts to further addressees, has been partially used. Thanks to this, in the end more than 100 experts from across Europe have been contacted, representing lighting experts from academia, research institutes, NGOs, manufacturers, lighting installers, lighting associations, municipalities, etc. In total, 29 experts provided data on LED projects in their countries and across Europe. In addition, the GreenLight Programme of the Joint Research Centre of the European Commission was used as a source of information.[3]

This article presents an analysis of 106 pilot projects selected from 17 European countries. The projects have been chosen by the experts addressed as representative and therefore, although all LED projects in Europe are not (and cannot be) represented, a good overview of the situation in Europe is provided.

The respondents were given a common formatted Excel sheet to be filled in for each LED project. However, in most cases, the project description did not follow the common format. The analyzed case studies, therefore, vary in both form and level of details provided by the respondents. That is why the article offers qualitative, rather than quantitative analysis (even though some quantitative data are provided).

A full list of all respondents that provided data on LED projects and a list of the analyzed LED projects together with references to more information are available in Valentová, Quicheron, and Bertoldi 2011).

Limitations

The sample for the analysis is not exhaustive. The aim was not to provide the full list of existing LED installations but to give a good overview of the LED projects around Europe — i.e., covering typical installations and their characteristics.

Statistical conclusions should not be derived from the article. For instance, the number of projects per country does not fully correspond to the distribution of the LED projects in Europe.

Seventeen countries are represented in the sample. This does not mean that there are no LED projects in the other European countries. It may mean that in those countries, data on LEDs are not systematically collected and the few projects realized so far are for testing purposes. The proportions between LED projects from different countries do not represent the real proportions of existence of LED projects around Europe.

The second type of limitation pertains to the information reported. The respondents have provided the LED projects' data. There is no check on the correctness of the data by the authors. This being said, for the projects coming from the GreenLight Programme (14 projects[4]), the reports undergo a double check – by the National Contact Points and by the Joint Research Centre – manager of the programme.

At the same time, the data have often been provided by the manufacturers themselves, or as showcases (good practice examples). This means, for instance, that the number of cases where drawbacks are described may be limited due to the character of the reports.

Led Projects – Overview

A total of 106 LED test cases have been collected from all over Europe. The projects come from 17 European countries – a quarter from Germany, 10 from Spain, and eight from Switzerland (Figure 1).

As shown in Figure 1, the number of test cases analyzed does not necessarily correspond to the number of buildings or facilities. In Belgium, the test case of Delhaize Company covers the installation of LEDs in 130 supermarkets. In Denmark, one of the test cases covers 69 Q8 gas stations, where neon lights have been replaced with LED lighting, and in Northern Alentejo in Portugal, LED lights have been installed in 12 municipalities. The data for these test cases have been provided as a summary and therefore are presented as one test case. Similarly, since 2007, more than 100 LED signs have been installed in 45 Coop shops in Italy, but the contact person selected only four test cases as representative ones, for which further data have been provided.

The LED technology is a relatively new one, at least in terms of commercial applications. Only two projects in the sample were carried out in 2003–2005. All the other projects were realized in the last five years (between 2006 and 2011). Almost 80% of the analyzed projects were carried out in the last two years, or are still ongoing.

A typical application for LEDs is outdoor public lighting installations. In the sample, almost two-thirds of the projects are

[2]Methods of economic calculations at lighting installations are described in detail in, for instance, Li et al. (2009).

[3]The GreenLight Programme is an on-going voluntary programme whereby private and public organizations commit toward the European Commission to reducing their lighting energy use, thus reducing polluting emissions. GreenLight was launched in February 2000.

[4]City of Koenigsfeld, City of Tilburg, Municipality of Piombino, Delhaize Belgium, Gemeinde Diex, Gemeinde St. Georgen, Hamburg Streetlights, Intesa SanPaolo, Nyborg Street lights and Nyborg gas stations, Unibail-Rodamco, City of Utrecht, Stadt Villingen Schwenningen, Vossloh-Schwabe Optoelectronic GmbH & Co. KG.

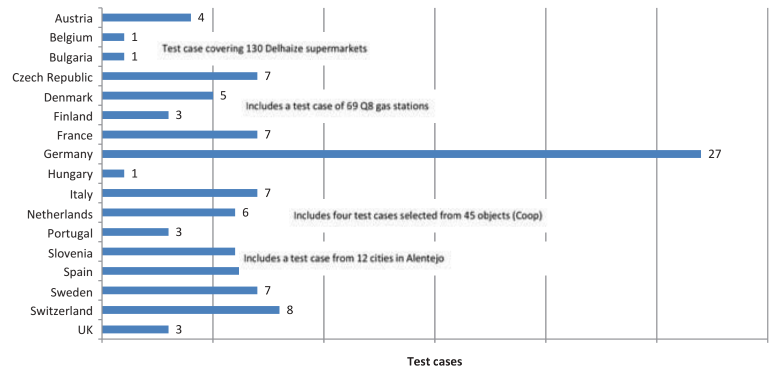

Fig. 1. Analyzed LED test cases per country.

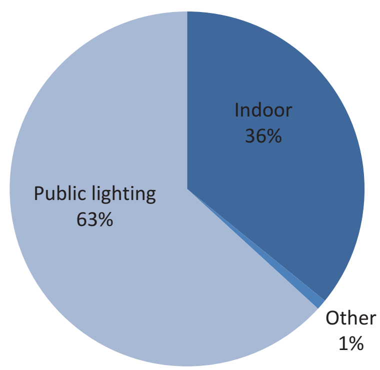

Fig. 2. Type of LED projects.

public lighting projects (Figure 2), which entail street and road lighting,[5] bicycle paths (three cases) but also traffic lights (five cases) and tunnel lighting (one case).

In the sample, LED lights are often used for lighting streets with less traffic, or for pedestrian and bike paths. According to the analyzed projects, current LED solutions do not seem to offer enough performance to ensure adequate lighting of streets and roads, acceptable to the safety authorities as well as population. However, the reduced light output of LEDs and their color can be an advantage for pedestrian spaces. In Darmstadt, Germany, the LED lights have been tried out specifically on a road with higher luminance needs and the results are satisfactory – the LEDs complying with the standards (Khanh 2010). This shows that the technology is evolving rapidly as cities use more and more LEDs for road lighting, as shown by the PLUS (Public Lighting Strategies for Sustainable Urban Places) project of the Lighting Urban Community International (LUCI) Association.

Indoor LED lighting projects (36%) are much more varied. The sample includes hotels, restaurants, shops and shopping malls, markets, gas stations, museums, theatres, and industry buildings too. In the shopping malls, the areas cover indoor parking lots, offices, or corridors. One project is about aviation safety lights, which were mounted on transmitters (antennas) of mobile operators.

In the United Kingdom, a large program on retrofit of social housing has been running. Several of the projects of complete house refurbishment included LED lighting. Two-phase trials of LED lighting in communal areas of social housing in England have been carried out from 2008–2010 (Energy Saving Trust 2011).

In several projects in the sample document, LEDs are installed in historical buildings. There is a historical building at the National Theatre in Prague, Czech Republic, built in the 19th century, in which LEDs replaced incandescent light bulbs in all emergency lighting. Similarly, LED lighting has been used in the Musikpavillon, Luzern, Switzerland, and also the Hunterian Museum in Glasgow, United Kingdom, the oldest public museum in Scotland, in which LED lights replace halogen spotlights (more about these examples are also given in the section on benefits).

Technology

The sample projects are quite diverse, and it is not easy to find a common denominator as to what technologies are replaced, and consequently what type of LED technology is used. The variability of LED lights, as one of their advantages, predisposes them to be a replacement for many different lighting technologies in different installations. Below, we present the types of replaced technologies found in the case studies reviewed.

In the indoor lighting projects reviewed in the study, among others, LEDs replace incandescent light bulbs (as in the case of emergency lighting in the National Theatre, Czech Republic, Christmas lighting in Solothurn, or, for instance, the Musikpavillon in Luzern).

More often, however, LEDs have been found to replace halogen low-voltage downlights (e.g., the Ribe Kunstmuseum in Denmark, the Hunterian Museum in Glasgow, United Kingdom, the Hotel Algarve in Portugal, or Delhaize Belgium, to cite a few). In the Marriott Hotel in Prague, Czech Republic, the LED lights replace the halogen lights on top of room entrances, another typical use of this technology and potential for replication.

[5]The difference in street and road lighting, as perceived in the projects, is in the level of traffic, where streets evoke residential areas or areas with less traffic (and consequently lower luminance needs). In this sense, street light projects largely prevail in the sample.

In a trial project of social houses in the United Kingdom, LEDs have been used to replace fluorescent tubes, which are on for 24 hours a day and therefore offer sufficient potential for energy savings. In eight of the 10 shopping malls in Spain (Unibal Rodamco, Spain), fluorescent tubes in indoor parking lots are replaced with LEDs.

In outdoor (public) lighting projects, the technology replaced is often the high-pressure sodium (HPS) lamps (e.g., street lighting in Lugano in Switzerland, Ljubljana in Slovenia, Regensburg in Germany, Espoo in Finland, and Freiburg im Breisgau in Germany). Rather less frequent are replacements of mercury vapor lamps, which are however much less represented in some countries (e.g., the Norrbackagatan project in Sweden, and Stuttgart or Darmstadt in Germany). The traffic lights projects usually entail replacement of incandescent light bulbs in the traffic lighting systems (e.g., City of Graz, Austria, Hamburg streetlights, Germany, or Northern Alentejo, Portugal).

In some cases, fluorescent tubes and compact fluorescent lamps (CFL) can be the competing technology. For instance, in Amsterdam, Tilburg, and Assen (the Netherlands) over 200 pilots with 6000 luminaires are reported, mentioning CFL as the competing technology. However, it does not seem that LEDs would directly replace CFLs. Instead, a comparison was made saying that up to 15% savings can be achieved in the public lighting projects, compared with CFL, due to better directionality. In Paderborn, Germany, the street lighting project involves the complete replacement of existing fluorescent lighting in more than 750 installations in the core urban area with LED lights. Similarly, in the road lighting project in Vienna, Austria, 58-W fluorescent tubes were replaced with LEDs. In the project of lighting refurbishment in social houses in the United Kingdom, the fluorescent tubes were replaced in communal areas, and in Spain also fluorescent tubes are the main technology replaced in 10 shopping malls.

In two cases, the technology replaced is neon lighting. The Q8 gas stations in Denmark replaced neon signs on many of their petrol station sites with LEDs. Vodafone in the Czech Republic replaced neon (and halogen) aviation safety lights installed on some 350 transmitters.

For some projects, the total number of light points in the installation decreases, as in the case of Gemeinde St. Georgen, Germany, where 124 light points, equipped with sodium and mercury-vapor lamps (with power from 75 to 165 W), were substituted by 64 light-point LEDs (with a power from 26 to 50 W).

Conversely, there are projects in which the number of lights installed increases. The reasons can be to maintain the level of luminance (as reported, for instance, in National Lighting Product Information Programme 2010), or simply because at the original state, only every third pole has a bulb, whereas the new state means luminaire on every pole (public lighting project in Sungurlare, Bulgaria).

The projects do not focus only on the lamps but also cover a complex renovation of the lighting system. Therefore, these frequently include digital control systems, motion detectors, occupancy controls, time scheduling, and other management features, which can bring additional energy and cost savings as well as comfort.

For example, in the Glasgow Hunterian Museum, Scotland, the whole system can be gradually dimmed when the area is unoccupied. The museum is divided into zones, each with sensors so that when a visitor leaves the zone, the lights are dimmed after a few minutes.

To sum up, projects show a wide variety of existing technology and replacement features, including number of lights installed and design of the lighting system. This will have an effect on energy savings and quality of light.

Energy Savings and Quality Aspects

The present section focuses on the benefits in terms of energy savings and quality of light, and additional co-benefits are described in Advantages and Co-benefits section.

From the 106 LED reviewed projects, 70 reported on energy savings achieved, either in absolute numbers (MW h/year) or in relative terms (%), or in both. However, for two projects, the calculation relates to the whole project, which also covered other lighting technologies, so it was not possible to separate the specific contribution of LEDs.

The relative savings in the projects reviewed average at 59% (without the two above-mentioned cases) and the total amount of energy savings reaches more than 14.4 GW h/year in the sample (from 38 projects). The proportion of savings ranges from 10 to 90%. It is higher in indoor compared to outdoor projects: for 12 indoor lighting projects, where this data were reported, the average savings reach 69% and for the 36 public lighting projects, the average savings are 55%. The sample, of course, is not large. However, it at least gives an indication of the levels of savings in these categories. In general, the relative savings in the sample are higher in cases where incandescent light bulbs are replaced (potentially up to 85 to 90% energy savings).

In many cases, the savings reported were not achieved only by the LED technology but also by other lighting energy efficiency measures such as occupancy and motion controls, time scheduling, or luminaire optimization. On the other hand, there are projects in the sample at which energy consumption (or installed power) is higher than at the original installation or higher than would be the best conventional technology.

For instance, there are trial projects currently being carried out in the city of Prague (Czech Republic) by several manufacturers. Each manufacturer selected for the project (in total there are six of them) has installed LEDs in one selected street. In three cases, the installed power of the system goes down; in three cases, the LED luminaire-installed power compared with the original technology is higher. The difference is due to differing technologies, different lighting characteristics of LEDs, and shapes by different manufacturers. The reason is most probably the trial character of this project. The main aim of the client – the city – is to monitor the qualitative characteristics of LEDs and their development over time, the maintenance needs, and their perception by drivers and pedestrians.

In the Delhaize retail stores in Belgium, the power of luminaires with LEDs is almost 70% lower than the original technology (low voltage halogen lamps). However, the number of luminaires has increased significantly, being now 3.5 times higher than the original state. Therefore, the total electricity consumption of the LED lighting system is 17% higher than it was before the replacement. Other measures in the supermarkets entailed replacement of 26-mm fluorescent tubes by 16-mm ones and replacement of magnetic ballasts by electronic dimmable ballasts and change of luminaire reflectors. The number of other luminaires (with fluorescent tubes and metal halide lamps) decreased significantly (in the case of metal halide lamps, four times). Therefore, the consumption of fluorescent tube luminaires decreased by almost 50% and that of metal halide luminaires by more than 90% (while lighting quality improved). Thanks to these measures, the project as a whole comes out with a payback period of less than three years.

Similarly, in the street lighting project in Nyborg, Denmark, high performance lamps (HPL) were replaced by CFLs. All the 42 new lighting fixtures further included a blue 5.5 W LED at the top, which gave an extra consumption of 0.97 MW h/year. Nevertheless, the overall electricity consumption of the whole system decreased by 73%, thanks to replacements of high-pressure lamps by CFLs.

In Darmstadt, Germany, a trial project has been carried out to test four lighting technologies – the original mercury vapor lamps, two HPS-based lamps, and LED lamps. LEDs are reported to provide savings of 35%, compared with the HPS lamps. The project report states, however, that the consumption is still 8% higher compared with the best conventional technology with electronic ballasts (Khanh 2011).

However, besides energy savings, the installation also needs to be assessed from the viewpoint of quality of lighting, quality and age of the original installation, and other criteria, which go hand in hand with the evaluation of savings. There are projects in the sample that reported on energy savings but at the same time quality of lighting decreased (see the section on drawbacks), which may not be a desirable situation.

Given the quick and continuous development in LEDs, and the unstable quality of different installations (see section on drawbacks and challenges), some of the test cases specifically highlight the fact that the given installation has fulfilled the relevant norms and standards on lighting. For instance, this is the case of the street lighting trial project in Darmstadt, the street lighting project in Rietberg, or in Hannover, all in Germany, the road lighting project in Budapest, Hungary, or the shopping malls in Spain.

Economics of Led Pilot Projects

From the 106 cases studies, 35 reported on economic effectiveness (in all cases the criterion was the payback time).

In 21 cases, the value of investment has been provided. However, this obviously differs among the projects that range from small-scale projects in retail to hundreds and thousands of lighting systems installed. Therefore, the investment costs range from hundreds of euros to several million euros.

The payback period in the cases reported varies from less than a year to about 10 years, with an average at 4.3 years (Figure 3).

In two cases (Delhaize, Belgium and the National Theatre, Czech Republic), the calculation relates to the whole installation, which also includes other types of lighting (such as CFLs or HPS etc.). In the Delhaize project, LEDs have been installed as part

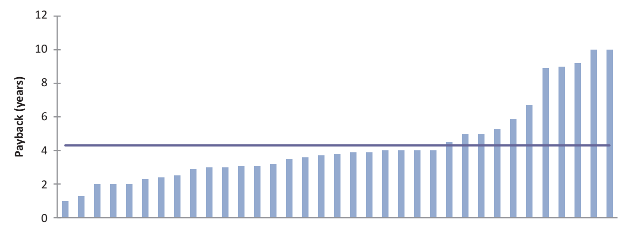

Fig. 3. Payback of 35 LED projects. Note: Dark blue line represents the average payback time of projects.

of a complex lighting renovation project. Lighting applications, with higher saving potential, provide a cushion for the less effective ones, and therefore the overall payback is 2.9 years. In the case of the Czech National Theatre, the overall payback time of the project, which entailed installation of CFLs, efficient halogen lamps, and LEDs, was two years.

Even though the sample for economics of the installations is rather small, there is a clear difference in the sample between the payback times for public lighting projects and indoor lighting projects. For street lighting (and traffic lighting systems), the average payback period (of 14 projects) is six years, whereas for indoor lighting projects, the average payback period (including offices and retail stores, in total 21 projects) is 3.3 years (Valentová, Quicheron, and Bertoldi 2011).

Some projects in the sample have been realized through an Energy Performance Contract (EPC)[6] or similar type of energy service contract. If an EPC is applicable for the project, it automatically implies cost-effectiveness of the project. In the project in the Czech National Theatre, LEDs were part of a larger, complex, and very successful EPC project. Energy Performance Contracting was also used in the case of the public lighting project in Sungurlare, Bulgaria. In Graz, Austria, incandescent bulbs in traffic lights were replaced by LEDs in a "Thermo-Profit Contract" of the Graz Energy Agency.

The economics of the projects has not been reported in almost 70% of the projects. The managers of the street lighting project in Stockholm, Sweden went as far as to point out that "even if the installation cost had been higher for the LED installation, it was the best solution, considering the attractiveness of the city" (Valentová, Quicheron, and Bertoldi 2011).

In the French city of Balma, a trial project on street lighting was implemented. The economics of the installation has not been advantageous. However, the results would have been different with different pole systems and spacing while the LEDs have been installed in the existing system.

Similar conclusions are provided by two studies carried out by the National Lighting Product Information Programme (National

[6]Energy Performance Contracting (EPC) is a proven and cost-efficient instrument for tapping existing energy saving potentials in the buildings sector. EPC is a contractual arrangement between the beneficiary and the provider of an energy-efficiency improvement measure, according to which the payment for the investment made by the provider is in relation to a contractually agreed level of energy efficiency improvement or other agreed energy performance criterion such as financial savings (European Commission 2011a).

Lighting Product Information Programme 2010, 2011). In the studies, life cycle costs of various streetlights for collector roads and local roads (High Pressure Sodium, Induction, and LED lamps) were calculated. Essentially, the illumination levels strictly had to follow the national standards for Roadway Lighting. Costs per mile were determined for each lighting source.

The studies found that the LED streetlights tested (for local roads) required 41% less to 15% more power per mile than the base case. Similar results were found for collector roads too. (National Lighting Product Information Programme 2010) The life cycle costs of the whole installation were dominated by the costs of the poles though. To put it simply, the pole spacing for LEDs needs to be more frequent in order to comply with the standards. Given that the average life cycle costs per mile for LEDs were 1.9 times higher than the base case (100 W HPS).

However, one of the conclusions of the study is that the standard may not be "meeting the needs of streetlight system owners" (Poole, 2011), as 75% of the streetlight system owners do not light their local roads according to PE-8 recommendations (which were used in the study, as there is no other national standard).

Life cycle costs have been calculated for a street lighting trial project in Kereva, Finland. LEDs replace high-pressure mercury lamps. The present value of the life cycle costs has been estimated at €41.6/road meter.[7] One of the conclusions is that the pole spacing is not optimal and should be considered when designing the lighting system. However, this is not always possible in real life cases (Thäkämö et al. 2012).

In several cases, the respondents specifically mentioned that the economics of projects has not been followed, as it is a trial/experiment project (e.g., the Municipality of Piombino in Italy, the French City of Balma, or street lighting project in Stuttgart, Germany), pointing out that only some of the LED projects are economically effective and such evaluations always need to go hand in hand with quality aspects of the installations (e.g., for street lighting compliance with the standard EN 13201 on road lighting).

The resulting increased road safety is one of the co-benefits of LEDs that are covered in next section.

Advantages and Co-Benefits

One of the most often mentioned benefits is the reduction of costs of operation and maintenance. About one-third of those respondents who described the benefits of the installation (about 66 case studies) explicitly mentioned that the comparative advantage of LEDs, over other technologies, would be the reduced operation and maintenance costs, which is mainly due to longer life-time of LEDs. The need to substitute the burnt-out or damaged lamps is much less frequent. In Solothurn, Switzerland, LED Christmas lighting has been installed. Before that, the city had to change one-third of Christmas lights every year, which no longer happens with LEDs.

In Hamburg, Germany, in total, 500 lighting signal systems will be changed, LEDs replacing incandescent light bulbs (at the time of writing, about 380 light signal systems had been replaced). While the incandescent light bulbs needed to be changed every year, the LEDs are to be changed only once every eight to 10 years. About 80% of the cost savings realized so far are maintenance cost savings (€580,000 per year from a total of €716,000 per year) (Valentová, Quicheron, Bertoldi 2011).

In the City of Graz, Austria, the traffic lighting system has been renovated, with the replacement of 190 traffic lights with LEDs. From the total €339,000 of cost savings, about 55% can be attributed to energy savings and the rest being reduced maintenance costs (Valentová, Quicheron, Bertoldi 2011). Nevertheless, unlike these two examples, the maintenance costs are rarely explicitly quantified in monetary terms.

Apart from energy savings, the test case reports often highlight "soft" co-benefits, which add to the potential of energy savings. These co-benefits include, among others the following:

1. Road safety for traffic lights
2. No UV radiation
3. Indoor and outdoor lighting quality, indoor ambience, and atmosphere
4. Variability in the design of LED applications, and
5. Environmental benefits

These co-benefits (supplementary to energy savings) are rarely quantified, possibly hardly quantifiable, yet apparently perceived as very important by the customers. Often, these are highlighted as the major benefits, outdoing the "direct" benefit of energy savings, which, as mentioned above, may not be sufficient to cover the higher investment costs of the projects.

In traffic lighting systems, an important co-benefit has been mentioned several times: road safety, which increases, thanks to higher reliability of LEDs in traffic lights. Similarly, the project of traffic lights replacement in the City of Norderstedt, Germany, reports that, in comparison to incandescent bulbs, the "sun phantom effect" is avoided. A slightly different case, but related to safety issues, is the street lighting project in Freiburg im Breisgau, Germany, which stresses that the new installation increased the sense of security, among other benefits.

Another important group of benefits, which have been mentioned in the case studies, could be summed up as "indoor and outdoor lighting qualities, improved ambience and atmosphere." The street lighting project in Toulouse, France, highlights the benefits of stable chromatic effect, whereas more uniformity in lighting is appreciated in the street lighting project in Lugano, Switzerland. In some projects, the overall improvement of lighting quality is reported (such as in the case of Prague's Marriott Hotel, the City of Tilburg in the Netherlands, or the Municipality St. Georgen in Germany). Pleasant, neutral light is the benefit perceived of street lighting projects in Havířov and Pardubice in the Czech Republic. Significantly improved color reproduction has been cited as one of the main advantages of the street lighting project in Freiburg im Breisgau, Germany, as well as Espoo, Finland. For the indoor projects, cafeterias and bars benefit from the improved atmosphere provided by LEDs.

[7] The costs include dismantling of old luminaires, installation, use, maintenance, and end-of-life. The purchase price may have been higher than average due to the size of the installation – only four pieces of luminaires.

Other co-benefits, mentioned in several cases, are that the LED lamps do not produce UV radiation on objects and have a low direct heat output. This has been appreciated, for instance, in the Hunterian Museum in Glasgow, reporting to be able to illuminate sensitive parts of their collection in an aesthetically much more pleasant manner, while certain ancient objects could be illuminated for the first time. Similarly, in Bern's Parliamentary Library, Switzerland, LEDs provide lighting of bookshelves and reading tables. For the books, the heat protection is important.

The following benefits have been reported from a chain of supermarkets (Coop in Oberwil, Switzerland). Thanks to the LED downlights, the products remain fresh for a longer time and overall the presentation of the food (and of other products) is perceived to be better. LEDs also provide more attractive color rendering to customers.

Light emitting diodes are also seen to open up a broad opportunity for design. In the above-mentioned Parliamentary Library in Bern, Switzerland, thanks to LEDs, the lighting could be unobtrusively incorporated into the interior design.

Drawbacks and Challenges

In 23 (out of 106) project reports, some drawbacks are mentioned related to LED installations.

In some cases, what has been reported as a benefit at one installation has been reported as a perceived drawback in another one.

1. *Uniformity of light*: For instance, in the City of Séquestre, France, a trial project was launched in 2007, testing LED street lighting at a roundabout. The project report concludes that while drivers and pedestrians generally welcomed the color of the light and little glare, the uniformity of light was not perceived very well; in contrast to other projects of street lighting, which highlight the uniformity of lighting as one of the strong points – Paderborn and Kieselbronn, Germany or Lugano, Switzerland. Similarly, the report on installation of LEDs at ski slopes in Kittilä, Finland, highlighted the functioning at low temperatures, unlike in the Swedish project in Kalix, where roadway tests were carried out and reported degradation of light sources at low temperatures.
2. *LED technology is not yet delivering high luminance*: In Stockholm (Akalla-provsträcka, Konradsbergsparken, and Katarinavägen) various problems related to lighting (luminance) quality have been spotted by the company that installed the lighting systems. For instance, in the Akalla-provsträcka project (Stockholm, Sweden), only four of the 10 tested LED fixtures gave the requested amount of light and only one passed all criteria. In another project, from the City of Stockholm, Konradsbergsparken, the LED fixtures give too little light, and light is perceived as gloomy and cold, making the space "uninviting." The same problem was also perceived in the Norrbackagatan project, Stockholm, where moreover too much unwanted backlight seems to be pointing toward the apartments. On the other hand, no light to surroundings is perceived as one of the drawbacks in Konradsbergsparken.

In Toulouse, France, low levels of lighting attained with LEDs was the reason for installing LEDs only in pedestrian zones so far (mentioning though that for pedestrians, the reduced luminance is actually more convenient).

3. *Poor quality of LEDs*: Another challenge (and one of the major ones) is the quality of LEDs, which according to some does not always meet the technical criteria that the customers require. In the Katarinavägen project, Stockholm, after two years the whole installation had to be changed due to manufacturing error in LED boards, and because of the the whole installation went dark for a period of six months. This is totally unacceptable for this type of installation, as public lighting needs to be reliable and easy to maintain, with spare parts readily available.
4. *Missing data from manufacturers*: In the Swedish Akalla-provsträcka project, the installers complained about gaps in information received from manufacturers and missing or incorrect data for fixtures. These concerns are also found from other sources (Poole 2011).
5. *Quality of the LED lights*, in general, is a chapter on its own. Poor quality of some LEDs is perceived as a major concern. Low-quality LEDs in the market give bad publicity to whole LED lighting and may discourage some system designers and the final users from using LEDs in future. One bad experience tends to discourage users for many years – a similar situation happened with CFLs some years ago (European Commission 2011b).
6. *New suppliers have reduced knowledge of LED products*: The evaluators of the LED project in Tilburg, the Netherlands, specifically highlight that "new suppliers with no public lighting experience are a risk and so is too much pressure from politicians to implement LEDs. A LED pilot has to be evaluated seriously to build up knowledge" (Wajer, Mackaay, and Ottens 2009).
7. *High initial investment cost*: In a number of projects, the high initial investment costs are perceived as a limiting factor (specifically reported, for instance, by Coop, Italy, Ribe Kunstmuseum, Denmark, and Galerie Forsblom, Finland). However, high initial costs are often offset by lower energy and maintenance costs, as reported in the section on economics.

Conclusions

Solid-state lighting is a fast developing technology with a high potential for development in future years. The growing number of projects all over Europe proves this trend. LED installations are highly variable and diverse, and so are their effects. These effects are complex to measure as they depend a.o. on the installed technology that is replaced with LEDs, the type of LED lights or fixtures used, the objective of the entity in charge of the project, and the criteria used to measure the performance of the test case.

However, from the 106 LED case studies reviewed in this article, the following conclusions are drawn, with a focus on energy efficiency:

1. LEDs can replace a great variety of lighting technologies, from high-pressure sodium and mercury vapor lamps in public lighting, through incandescent lamps in traffic lights or indoor applications to fluorescent tubes or halogen (spot)

lights indoors. In some instances, LEDs can also replace CFLs.

2. Given the variability of installations, the resulting energy savings range from 10% to as much as 90%. In some cases though, the energy consumption is higher than with the original technology.
3. In many applications, LEDs are competitive (offering payback time from 2 to 10 years).
4. In a large number of projects (trials and test cases), the economics are not relevant, not measured, or would not be advantageous. Yet, all applications show a clear potential for competitiveness in the (near) future.
5. It seems that the results of the projects are highly dependent on the specific features and conditions of each installation. Given the great variability in LED installations, what may have worked in one application may not be the most suitable and optimal one for another application.
6. There are several common success factors for replication in the current state-of-art, such as replacement of incandescent light bulbs in traffic light systems or specific installations in retail stores and shops, e.g., replacing halogen spotlights.
7. Main co-benefits of the LED projects analyzed are as follows:

- Lower maintenance costs
- Improved atmosphere and lighting characteristics, no UV radiation and flexibility in design
- Improved security (road safety)
- Contribution to climate change goals and environmental protection

Some drawbacks were also perceived by the respondents:

- LED quality characteristics (uniformity of light, glare, etc,)
- Information and data provided by the manufacturers/suppliers
- LEDs may not be the optimal solution for the existing street lighting systems (e.g., given the pole spacing)

The number of LED installations is growing fast. Most of the projects reviewed in this study are reporting substantial benefits, be it on energy (and money) savings or having impact on the environment. Nevertheless, some challenges remain. Wajer, Mackaay, and Ottens (2009) sum it up by calling for the implementation of “coordinated neutral pilots before changing over to LED solutions for public lighting on a wide scale.”

Careful evaluation of the existing projects and exchange of information on the good practice examples, as well as on bottlenecks and risks, may be a way to facilitate expansion of LEDs. In the meantime, the quality characteristics of LEDs – via the setting up of standards and their enforcement – and provision of proper data by manufacturers are among the main challenges.

Acknowledgments

The authors would like to thank all the respondents who kindly provided details on LED test cases as well as those who provided further contacts. This work was done in the context of the European Commission study “Preparing for the wide deployment of Solid State Lighting (SSL) in Europe” (SMART 2011/0069) in cooperation with the European Commission’s Photonic Unit (DG Information Society and Media).

References

Adkins, E., S. Eapen, F. Kaluwile, G. Nair, and V. Modi. 2010. Off-grid energy services for the poor: Introducing LED lighting in the Millennium Villages Project in Malawi. *Energy Policy* 38:1087–97.

Bertoldi, P., and B. Atanasiu. 2008. Characterization of residential lighting consumption in the enlarged European Union and policies to save energy. *International Journal of Green Energy* 5:15–34.

Dubois, M.-C., and A. Blomsterberg. 2011. Energy saving potential and strategies for electric lighting in future North European, low energy office buildings: A literature review. *Energy and Buildings* 4:2572–82.

Dupuis, R.D., and M.R. Krames. 2008. History, development, and applications of high-brightness visible light-emitting diode. *Journal of Lightwave Technology* 26(9):1154–71.

Energy Saving Trust. 2011. *Lit Up: an LED lighting field trial 2011*. Report. Available at http://www.energysavingtrust.org.uk/Publications2/Energy-efficiency/Lit-Up-an-LED-lighting-field-trial, accessed May 2012.

European Commission. 2011a. *Directive of the European Parliament and the council on energy efficiency and repealing directives 2004/8/EC and 2006/32/EC*. COM(2011) 370 final. European Commission, Brussel, Belgium.

European Commission. 2011b. *European LED quality charter*. An initiative promoted by the European Commission Joint Research Centre, Brussel, Belgium.

European Commission. 2011c. *Lighting the future: accelerating the deployment of innovative lighting technologies*. Green Paper, COM(2011) 889 final, European Commission, Brussel, Belgium.

Huang, B.J., M.S. Wu, P.C. Hsu, J.W Chen, and K.Y. Chen. 2010. Development of high-performance solar LED lighting system. *Energy Conversion and Management* 51:1669–75.

Khan, N., and N. Abas. 2011. Comparative study of energy saving light sources. *Renewable and Sustainable Energy Reviews*, 15:296–309.

Khanh, T.Q. 2010. *Umrußstung einer ME2-Straße mit LEDs*. Technical University Darmstadt, Germany.

Khanh, T.Q. 2011. *LED-Teststrecke in Darmstadt*. Technical University Darmstadt, Germany.

Li, D.H.W., A.H.L. Mak, W.W.H Chan, and C.C.K. Cheng. 2009. Predicting energy saving and life-cycle cost analysis for lighting and daylighting schemes. *International Journal of Green Energy* 6:359–70.

National Lighting Product Information Programme. 2010, September. *Streetlights for collector roads*. Specifier Report 13, No. 1 (Rev. 2, November 2010), Rensselaer Polytechnic Institute, New York, NY.

National Lighting Product Information Programme. 2011, February. *Streetlights for local roads*. Specifier Report 14, No. 1, Rensselaer Polytechnic Institute, New York, NY.

Pode, R. 2010. Solution to enhance the acceptability of solar-powered LED lighting technology. *Renewable and Sustainable Energy Reviews* 14:1096–103.

Poole, S. 2011. Standardized testing of SSL products – contradictions, challenges, and lessons learned. *Proceedings of the LED lighting summit*, 4–5 May 2011, Berlin, Germany.

Richards, M., and D. Carter. 2009. Good lighting with less energy: Where next? *Lighting Research and Technology* 41:285–6.

Ryckaert, W. R. K.A.G. Smet, I. A. A. Roelandts, M. Van Gils, P. Hanselaer. 2012. Linear LED tubes versus fluorescent lamps: An evaluation. *Energy and Buildings*, doi:10.1016/j.enbuild.2012.02.042.

Teng, T.-C. 2013. A novel design for a fluorescent lamp with an air cleaning function and better lighting efficiency. *International Journal of Green Energy* 10:661–79.

Thäkämö, L., A. Ylinen, M. Puolakka, and L. Halonen. 2012. Life cycle cost analysis of three renewed street lighting installations in Finland. *The International Journal of Life Cycle Assessment*. 17(2):154–64.

Valentová, M., M. Quicheron, and P. Bertoldi. 2011. *LED projects and economic test cases in Europe*. Prepared under SMART 2011/0069. Petten: Joint Research Centre – European Commission, 38 p.
Wajer, B.H., T. Mackaay, and J. Ottens. 2009. "Energy labels and LED solutions change public lighting." In *Proceedings of ECEEE* 2009 *summer study. Act! Innovate! Deliver! Reducing Energy Demand Sustainably*, ed. C. Broussous and C. Jover. Stockholm, Sweden: ECEEE.pp. 493–8.
Yang, J.-P., and H.-C. Hsiao. 2006. The design of a new energy-conservation type solar-powered lighting system using a high-pressure sodium lamp. *International Journal of Green Energy* 3:239–55.

ANNEX 4

'Designing Energy Efficiency Subsidy Programmes: The Factors of Transaction Costs' *(Valentová, Lízal, and Knápek 2018)*

Energy Policy 120 (2018) 382–391

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Designing energy efficiency subsidy programmes: The factors of transaction costs

Michaela Valentová*, Lubomír Lízal, Jaroslav Knápek

Czech Technical University in Prague, Faculty of Electrical Engineering, Technická 2, 166 27 Prague, Czech Republic

ARTICLE INFO

Keywords:
Transaction costs
Energy efficiency
Policy evaluation

ABSTRACT

Transaction costs are perceived as one of the main barriers in achieving energy efficiency. Hence, the omission of transaction costs in the evaluation (and preparation) of energy efficiency policies leads to suboptimal decision-making. However, empirical evidence on the main factors influencing transaction costs of energy efficiency programmes remains insufficient. By investigating two cases of major energy efficiency subsidy programmes in the Czech Republic, we analyse the role of two factors influencing the transaction costs: size of the projects and type of actors. The results show that while the dependence between the size of the projects and the size of transaction costs is rather straightforward, the role of actors is more complex. On one hand, no significant difference has been found between total transaction costs of the two types of actors entering the analysed programmes (private companies and public entities). Our results imply the potential for optimization of transaction costs in energy efficiency subsidy programmes lies in streamlining the internal processes (especially in the preparatory phase and in public tenders) and a clear legal environment. On the other hand, differences between the two entities were found in the costs of external services, indicating a room for optimization for public bodies.

1. Introduction

In 2010 the European Commission launched the Europe 2020 initiative, which sets ambitious targets to be reached by 2020. Among others, a 20% increase in energy efficiency should be attained (European Commission, 2010). The Energy Efficiency Directive (European Parliament and Council, 2012), adopted in 2012, sets out a further set of binding measures that should help the EU Members States reach the energy efficiency target. It requires that energy distributors or retail energy sales companies (or the Member States, if they opt for so-called alternative policy measures) achieve 1.5% energy savings per year through the implementation of energy efficiency measures. Furthermore, 3% of the total floor area of heated and/or cooled buildings owned and occupied by the EU Member State central governments has to be renovated each year.

The European Union supports its Member States in achieving the goals by providing a substantial level of funding through its Cohesion Policy programmes. In the programming period 2007 – 2013 a total of EUR 6.1 billion was allocated to the priority theme “Energy efficiency, co-generation and energy management”, representing 2% of the total allocation (Ramboll and Institute for European Environmental Policy, 2016). Furthermore, the theme “Enterprise” (under which energy efficiency improvements have also been co-funded) was supported with EUR 51.9 billion, i.e. about 20% of total ERDF and Cohesion Fund support in the EU during the 2007 – 2013 period (Applica and Ismeri Europa, 2016).

Given the ambitiousness of the goals and the significant levels of expenditures allocated to reach them, it is crucial that careful evaluation (ex-ante and ex-post) is carried out in order to ensure that the public money is spent effectively. Transaction costs of the programmes are one of the main aspects of such assessment. The negative impact of transaction costs on the implementation of energy efficiency measures has been acknowledged and supported by a number of studies (Ostertag, 1999; Reddy, 1991; Sanstad and Howarth, 1994). Transaction costs can impede the implementation of energy efficiency policy measures or even prevent them from being implemented at all (Mundaca et al., 2013). Even though transaction costs cannot be zero (from the mere reason of existence of economic activity (Cheung, 1998)), it is believed that lower transaction costs are”almost always beneficial” (Gu and Hitt, 2001).

When designing energy efficiency policies, transaction costs are often not systematically taken into account and are not systematically evaluated ex-post (McCann et al., 2005). North (1990) categorises transaction costs to market costs (such as legal fees) and costs of time that the actors spend to gain the necessary information. Importantly, the transaction costs always consist of a variable part (dependent on the

* Corresponding author.
E-mail addresses: michaela.valentova@fel.cvut.cz (M. Valentová), lubomir.lizal@cvut.cz (L. Lízal), knapek@fel.cvut.cz (J. Knápek).

https://doi.org/10.1016/j.enpol.2018.04.055
Received 29 March 2017; Received in revised form 28 February 2018; Accepted 24 April 2018
0301-4215/

size of the project) and fixed part (independent of the size of the project) (Musole, 2009). The specific categorisation then tends to be case specific. Michaelowa and Jotzo (2005) for instance identified costs of monitoring as fixed costs and costs of negotiation as variable costs. The typical phases during which the transaction costs of energy efficiency programmes arise would be planning, implementation and monitoring and verification (Mundaca et al., 2013; Rao, 2003).

The empirical evidence on the transaction costs of energy efficiency programmes is still inadequate, and in particular, the number of quantitative estimates is limited (McCann et al., 2005; Mundaca et al., 2013).[1] In the available studies, transaction costs are of non-negligible levels. For instance, Jaraitė et al. (2010) estimated the transaction costs of three programmes aimed at efficient transport. They found that the transaction costs ranged from 3% (of total costs of a fuel efficiency programme) to over 18% (of compliance costs of the Fuel Label Program). Björkqvist and Wene (1993) analysed the transaction costs of energy efficiency measures in households. They estimated the level of transaction costs at 28% of the level of energy efficiency investment (using gross labour to express the transaction costs). Mundaca (2007a) analysed the white certificates scheme in the United Kingdom, estimating the transaction costs at 8–12% of the investment in lighting and 24 – 36% of the investment costs for insulation. Falconer and Whitby (2000) analysed the administrative costs of agro-environmental schemes in 8 European countries. The administrative costs varied from 6% to 87% of the compensation costs. Nevertheless the studies are usually not directly comparable as they differ by their focus (different policy programmes), by the method used to study the transaction costs (the choice of at which stage and on which actors the transaction costs are measured), and by the choice of indicator that the transaction costs are compared to.

It seems that transaction costs can to some extent be lowered thanks to the effect of a “learning curve” (Lee and Han, 2016; Michaelowa and Jotzo, 2005). However, the extent to which this is possible may depend on the character of transaction costs (Kiss, 2016). Various studies (Jaraitė et al., 2010; Michaelowa and Jotzo, 2005; Sathaye and Murtishaw, 2004) have concluded that transaction costs depend on the size of the project (or energy efficiency measure), i.e. the bigger the project, the lower the burden of transaction costs.

The key drivers that influence the size and structure of transaction costs have been summarised by, e.g. (Coggan et al., 2010; Mundaca et al., 2013; Musole, 2009). Among others, the actors of the transactions (projects) are one of the main drivers. Ahonen and Hämekoski (2005) found dependence between the transaction costs and the “competence and capacity of project developer”. Coggan et al. (2013) identify the characteristics of the transactors (their experience, capacity to assess information, etc.) as one of the core factors influencing the structure and level of transaction costs. Relatedly, the institutional environment and internal rules, in which the actors carry out the transactions, adds to the defining factors of transaction costs (McCann, 2013; Shahab et al., 2018).

This article, therefore, aims at partially filling this gap and focuses on the role of the actors on the size and structure of the transaction costs of energy efficiency programmes. Using qualitative and quantitative analysis it studies the transaction costs of two major energy efficiency subsidy programmes in the Czech Republic. In the Czech Republic, the allocation to energy efficiency policy measures amounted to roughly EUR 1.03 billion in 2007–2013 (Ministry of the Environment, 2007; SEVEn, 2010). Besides having distributed substantial amounts of financing to energy efficiency, the two analysed operational programmes are optimal for the research as they coincide in their main characteristics (type of subsidised projects, size of the projects, administration processes). Therefore, the only major factor in which the two programmes differ are the actors – the eligible applicants (public bodies and private entities). Furthermore, given their size (and the number of subsidised projects), the two programmes provide a solid base for research, and as they are part of the EU Cohesion Policy, there is potential for replicability of the research and findings in other countries and the current and future programming periods.

Based on the current state of knowledge on the factors influencing the transaction costs, the research question has been translated into two main research hypotheses. The **first hypothesis** is that the size of transaction costs is not fixed and depends on the size of the subsidised project. The **second hypothesis** states that the level and structure of transaction costs differ according to the type of actor carrying out the project.

The structure of the article is as follows. Section 2 describes the analytical background of the research, embedding the research within the conceptual framework of transaction costs theory and providing a detailed description of the methodological approach. In Section 3, the results of the analysis are presented, with a focus on testing the two main hypotheses on the relation between transaction costs and the size of the project and the actors. Section 4 assesses and discusses the main findings and embeds them in a broader context. Section 5 concludes and conveys policy implications.

2. Theoretical framework

2.1. Concept of transaction costs

Transaction costs are perceived as one of the main barriers to efficiency. As to e.g. (Schleich and Gruber, 2008), such statement can be extended to energy efficiency measures, too. The transaction costs theory is imbedded in the New Institutional Economics theory which stipulates that all actors in an economy make their decisions with bounded rationality (Musole, 2009). That means that all transactions (and contracts) induce transaction costs. Not including transaction costs in the decision-making leads to suboptimal decisions from the systemic point of view as a non-negligible part of the reality is neglected.

However, there is not an academic consensus on a standard definition of transaction costs (Musole, 2009; Ostertag, 1999). Also, the methods used to measure transaction costs differ in different studies and are tailored to the specificities of the studied policies and measures (McCann et al., 2005; Mundaca et al., 2013; Musole, 2009).

A definition that is suitable for this article is the one adopted by Mundaca (2007) and derived from Matthews (1986), which identifies transaction costs as the costs of preparation of a contract (ex-ante costs) and its implementation, monitoring and enforcement. Such a definition fits the studied energy efficiency subsidy programmes. In line with McCann et al. (2005), transaction costs also comprise administrative costs.

Björkqvist and Wene (1993) further highlight the need to consider the time of the ones who rejected or were unable to participate in the innovation (energy efficiency measure) in order to assess the effectiveness of the given demand side management programme. In the analysis presented in this article, such an assumption is extended to rejected, unsuccessful applicants.

2.2. Model of transaction costs

Transaction costs were examined in two particular subsidy programmes financed from the European Cohesion policy in the period 2007 – 2013: Operational Programme Environment (OP E, specifically Priority axis 3 focused on energy efficiency) and Operational Programme Enterprise and Innovation (specifically the ECO-ENERGY programme). Running under the same framework umbrella (the Cohesion funds), the two programmes had similar administrative procedures. They both focused on subsidising a broad range of energy

[1] In the Czech Republic, Lízal et al. (2001) analysed adjustment costs of investments in the Czech Republic, their general specification can be viewed as another approach evaluating the transaction costs.

efficiency measures in buildings, including thermal properties of buildings, technological measures, and other. The only substantial difference between the two programmes were the eligible subsidy recipients: public organisations (OP E) and private enterprises (ECO-ENERGY). The two programmes are described in detail in (Valentová, 2013).

The data were collected based on mixed method research. The reason is that this method combines the advantages of both quantitative and qualitative research methods (Creswell and Plano Clark, 2011). In line with this method, firstly qualitative research provides initial ("exploratory") information on the given topic. Based on this knowledge, quantitative research is carried out, that should test, generalise, and support the initial findings.

The research was conducted in three stages: desk research, structured interviews and a questionnaire survey. A similar approach has been already used by, e.g. Ofei-Mensah and Bennett (2013). Firstly, the desk research allowed the study of the primary documents of the subsidy programmes, such as the programming documents, that contain information on the administrative structure of the programmes and therefore provide a solid initial picture of the functioning of the programmes and the main steps in the whole administration process.

Secondly, semi-standardised in-depth interviews with subsidy recipients were carried out (as the qualitative part of the research). In total, eight subsidy recipients were interviewed (four for each programme) and two representatives of the administrative bodies. All the interviews were carried out in July – October 2011. The interviewees were selected from the whole population of applicants in a way to represent the structure of the population of the subsidy recipients in the given programme. The structure and sources of transaction costs were identified based on the desk research and confirmed and specified during the semi-structured interviews. In turn, the interviews helped to explain the findings from the questionnaire.

A question arises whether more qualitative interviews may have brought further themes (i.e. stages of the administration process, external costs of administration) to be then tested in the quantitative survey. In other words, the question is whether some topics may have been omitted. Galvin (2015) provides guidance for this reflection. He calculates the probability of a theme being present in a given sample of interviewees with respect to the percentage of the target population in whom the theme exists. For eight interviewees, there is an 83% probability of finding a topic that is represented in 20% of the population and 73% probability of finding a theme that is represented only in 15% of the population (see Annex B in (Galvin, 2015)). For themes represented in higher percentages of the population, the probability reaches above 90%. Apart from subsidy recipients, the project administrators (representatives of the administrative bodies) were interviewed. Even though the main aim of these interviews was to get information on the processes of the administrative body itself, being in daily contact with the subsidy recipients, the project officers also helped to identify and assess the processes of subsidy recipients. In line with (Galvin, 2015) this further helps to ensure that all relevant topics have been rightly and fully covered.

Thirdly, based on the interviews, a questionnaire was distributed among subsidy recipients (the quantitative part of the research). The questions were categorised in four main parts: 1) type of subsidised measures and general experience with the administration process, 2) time dedicated by the recipients to respective phases of the subsidised project's administration, 3) recipients' expenditures on external services connected with the subsidy administration and 4) their own experience, comments and opinion on the subsidy programme. The example of the questionnaire for ECO-ENERGY is in Annex A. In total, 463 subsidy recipients were contacted and 125 of them fully completed the questionnaire – 84 for OP E and 41 for ECO-ENERGY (a total response rate of 27%).

From those, only the respondents with one project were selected for further analysis. Even though respondents were asked to estimate the costs and time for all the projects together, given the character of the costs (and the fact that some of the respondents managed more than ten projects within the subsidy scheme), this step was taken to ensure comparability. As a result, a total of 55 responses for OP E and 35 responses for ECO-ENERGY were used in the further analysis.

In line with, e.g. Björkqvist and Wene (1993) the estimated time that the respondents devoted to the subsidy administration was converted into monetary terms through total labour costs. It is assumed that all the costs are incurred within one year. This simplifying assumption is based on the interviews with respondents (Eq. (1)).

$$C_t = h \times L \tag{1}$$

where C_t are the costs of time induced by subsidy administration, h is the estimated time spent on subsidy administration, L are the total costs of labour.

In the next step, the costs for external services connected with subsidy administration are added to the costs of time, which gives the total costs of subsidy administration in the given organisation (Eq. (2)).

$$TC_R = C_t + C_e \tag{2}$$

where TC_R are total transaction costs for individual subsidy recipients, C_e are costs of external services connected with the subsidy administration.

Total costs are then related to the total amount of the given subsidy, giving a percentage formula of the recipients' transaction costs so that projects of different sizes can be compared (Eq. (3)).

$$c_R = \frac{TC_R}{S} \times 100\% \tag{3}$$

where c_R is the percentage share of transaction costs on subsidy for individual recipients, S is the allocated subsidy for individual recipients.

The respondents were selected only from the successful recipients, as the list of unsuccessful subsidy applicants is not available.

Two main research hypotheses were formulated. The **first hypothesis** is rather straightforward (following, e.g. (Jaraité et al., 2010; Michaelowa et al., 2003; Mundaca et al., 2013; Musole, 2009)) and states that the level of transaction costs depends on the size of the subsidised project. The **second hypothesis** (following, e.g. (Coggan et al., 2013)) states that level of transaction costs depends on the type of actor carrying out the project.

A simple model was established to test the two hypotheses. The size of the subsidy of the project and the type of the programme are the independent variables and the transaction costs related to the project are the dependent variable.

$$TC_R = f(S; P) \tag{4}$$

where TC_R are the total transaction costs for individual subsidy recipients, S is the allocated subsidy for individual recipients, P is binary variable defining the type of programme being analysed for the individual subsidy recipients (i.e. the type of actor: private company in ECO-ENERGY and public body for OP E).

Regression analysis was used to establish the relationship between the variables TC_R, S and P. Firstly, regression analysis was run for the two samples separately, splitting the data by the type of the programme. This shows the relation between the two variables: the size of the subsidy and transaction costs. The dataset has a lognormal distribution.[2] Therefore, the regression was operationalized as:

$$\text{for ECO-ENERGY:} \quad lnTC_{R1} = \alpha_1 + \beta_1 lnS_1 + \varepsilon_1 \tag{5}$$

$$\text{for OP E:} \quad lnTC_{R2} = \alpha_2 + \beta_2 lnS_2 + \varepsilon_2 \tag{6}$$

where ε_i are the standard i.i.d. error terms, i = 1,2. The same regression

[2] We provide the evidence for treating the distribution as log normal in the next section.

equation can also be established for the relation between the total subsidy (S) and costs of time (C_t) and costs of external services (C_e) of the subsidy recipients.

To answer the second hypothesis of the paper – whether the transaction costs differ due to different actors, two null hypotheses have to be tested to assess the elasticity:

1) H_0: $\boldsymbol{\beta_1} = \boldsymbol{\beta_2}$, and
2) H_0: $\boldsymbol{\alpha_1} = \boldsymbol{\alpha_2}$,

A dummy variable D (where ECO-ENERGY was coded 1 and OP E 0) was introduced, to test these hypotheses:

$$ln(TC_R) = \alpha_2 + (\alpha_1 - \alpha_2)D + \beta_2 \ln(S) + (\beta_1 - \beta_2)D\ln(S) + \varepsilon \quad (7)$$

A regression function is developed and the coefficients ($\boldsymbol{\alpha_1 - \alpha_2}$) and ($\boldsymbol{\beta_1 - \beta_2}$) tested to be equal to zero. If the differences of coefficients are statistically significant, it means that these are different from zero and therefore there are statistically significant differences between α_1 and α_2, and between β_1 and β_2. The test of equality of variances of standard errors on standard confidence levels was also conducted.[3]

On the side of the administration body, the administrative costs associated with the administration of the subsidy programme were approximated through so-called technical assistance. Each operational programme is divided into so-called “priority axes”, which further specify the supported themes. Technical assistance is a subpart of all operational programmes and is represented as one specific priority axis in each programme. It is allocated to ensure implementation of the programmes. Administrative intensity was therefore estimated as the share of costs allocated to technical assistance for the given programme divided by the total allocation of the programme within the rest of the (substantive) priority axes in the programme, which define the supported types of projects (i.e. all priority axes except priority axis technical assistance). It is assumed that the technical assistance is distributed proportionally across the specific subsidised themes (priority axes) within each programme (Eq. (8)).

$$AI = \frac{TA}{S_{PA}} \times 100\% \quad (8)$$

where AI is the administrative intensity of the programme, TA are the costs allocated to technical assistance for the programme, S_{PA} is the total amount of financing allocated to subsidised themes (priority axes) of the programme, except technical assistance.

2.3. Limitations

The method employed has several limitations that need to be taken into account when discussing the results. The method does not include overheads (such as rental costs, electricity costs, administrative staff costs, etc.) attributable to the management of the subsidy. The in-depth interviews revealed that the accounting practice for overheads differed across companies and public bodies and therefore the obtained data would not be comparable. Therefore, only the direct staff working on the subsidy administration on the side of the recipient was included.[4] Furthermore, the subsidy recipients do not keep track of the hours allocated to subsidy administration and therefore the hours spent on different stages of the subsidy administration had to be estimated. The method used was similar to that used by, e.g. Hein and Block (1995), and Ofei-Mensah and Bennett (2013).

It is also assumed that the whole administration of the subsidy takes place within one year. The interviews revealed that in the studied subsidy programmes, all of the subsidy administration and implementation does take place within one year, except the monitoring reports that are to be submitted several years after finalisation of the project. However, the portion of the transaction costs related to the monitoring reports is so small that such a simplification could be made in this case. Relatedly, it is assumed that the administration costs (of the administration body) are evenly distributed across the priority axes and also across individual projects.

While the respondents estimated the time spent on the activity, they were reluctant to provide data on actual labour costs. Therefore, similarly to, e.g. Björkqvist and Wene (1993) the labour costs had to be approximated through general statistical data on wages and labour (and other costs directly related with the wages such as social and health insurance) in the given economic sector.

Additional limitation lies in the very research instrument, the questionnaire. It is not possible to influence who responds to the questionnaire. Therefore, the analysed sample can be best characterised as the sample of successful applicants that replied to the questionnaire. To partially make up for this limitation, a comparison between the survey population of successful applicants and the sample based on the main characteristics, such as the level of subsidy, type of applicant, type of facility and type of measure, was made.[5]

3. Results

Transaction costs were analysed for the two main energy efficiency subsidy programmes in the Czech Republic: Operational Programme Environment (specifically Priority axis 3 focused on energy efficiency, hereafter referred to as OP E) and Operational Programme Enterprise and Innovation (OPEI, specifically the ECO-ENERGY programme, hereafter referred to as ECO-ENERGY). The programmes were running in the years 2007 – 2013.

3.1. Transaction costs of the applicants

The following main phases of the subsidy administration process were identified in which transaction costs arise. Where differences between the two programmes occur, this is highlighted in the description.

3.1.1. Initial information and decision about the project

At this stage, the prospective applicant finds initial information on the subsidy programme and the conditions of the subsidy allocation. The decision on applying has to be made. The process depends on the type of the applicant. For private companies, this step mainly entails presenting the proposal to the company's management, for public entities it means preparing and presenting the background documents to the municipal council or similar body and its approval.

3.1.2. Submission of the subsidy application

After the decision has been made, the applicant prepares and submits the subsidy application. Some of the applicants hire an external company to help them with the subsidy administration. In some cases, *public tenders* for such external services are organised. The subsidy application consists of an online application form and paper documents. In the case of ECO-ENERGY, the application is a two-stage process. Firstly, the so-called *registration application* is submitted (serving as a preliminary filter for the projects). Upon approval of the registration application, the *full application* is submitted.

3.1.3. Project implementation (including public tenders for suppliers)

Once approved, the subsidised project is prepared and implemented. Following the conditions of the programme and the applicable laws, public tenders need to be organised for suppliers of the technology and other measures. The transaction costs connected with

[3] The tests show that in the logistic specification the error terms have equal variance on any convention level of significance; yet another fact supporting our specification.

[4] For instance, Prušvic (2006) identified the costs of the “overhead” employees to be 20 – 25% of the costs of “direct” staff.

[5] More details on the comparison are provided in (Valentová, 2013).

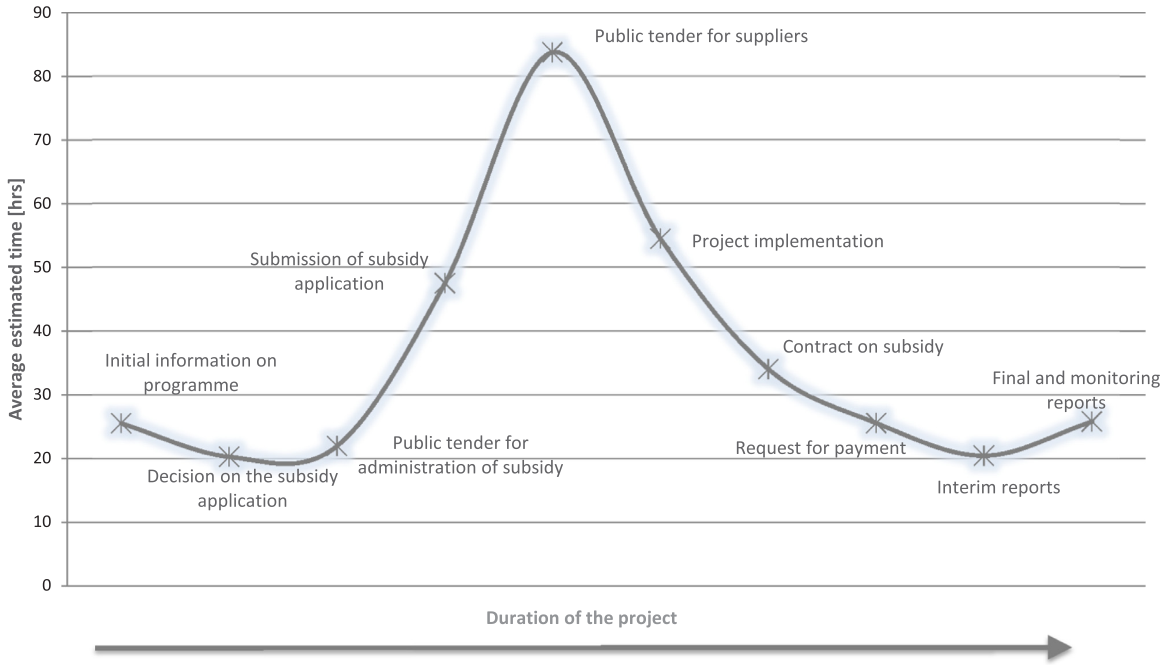

Fig. 1. Amount of time of individual phases of the administration process of the subsidy recipient – OP E.

the realisation of the project are the ones related to the fact that the project is subsidised. They mainly consist of the need to consult changes in the project or eligibility of expenditures with the administration body (i.e. whether these are eligible costs under the subsidy programme).

3.1.4. Contract on subsidy and request for payment

When the subsidy is approved, the contract between the administration body and the subsidy recipient is prepared and signed. Only after that is the subsidy recipient allowed to submit the request(s) for payment of the eligible expenditures connected with the project.

3.1.5. Interim, final and monitoring reports

The subsidy recipients have to regularly submit reports to the administration body. Those include interim reports throughout the realisation of the project, a final report at the end of the project and yearly monitoring reports for four years after the end of the project.

The following figures (Figs. 1 and 2) illustrate the whole administration process and the average amount of time of each stage of the process as estimated by respondents of the questionnaire survey.

The analysis has shown that the most time intensive phases are the processes connected with the preparation of the subsidy application and then the public tender for suppliers of the subsidised energy efficiency measures. Altogether from the initial information on the programme to submission of the application, the respondents spent on average 115 (OP E) and 195 h (ECO-ENERGY). Furthermore, they spent on average 84 and 120 h respectively on preparation and organisation of the public tenders. In total, the respondents estimated the time spent on administration of the subsidy to average 324 (OP E) and 494 h (ECO-ENERGY).

Apart from their own time, the respondents all stated that they outsourced some of the tasks connected with subsidy administration. All but one respondent said they hired an external company to prepare an energy audit (one of the compulsory parts of the application) and also more than 80% had the project documentation prepared by external companies. More than 60% had an external company helping to prepare the application as such. Two-thirds of the respondents in OP E (i.e. public bodies) hired an external company to prepare the tender dossier for the public tender for suppliers of energy efficiency measures, whereas the same applies only to 39% of ECO-ENERGY respondents (i.e. private companies).

The relative transaction costs of the subsidy recipients in the sample average 5.9% of the subsidy for OP E (with the maximum reaching 31% and median 6.7%) and 7.4% for ECO-ENERGY (with the maximum of 53% and median 11.5%). It means that for each EUR 100 of a subsidy, the recipients spent on average EUR 5.9 for OP E and EUR 7.4 for ECO-ENERGY on transaction costs connected with the subsidy. The main results are summarised in the following Table 1.

For unsuccessful applicants, the data are not available. If we approximated the transaction costs of unsuccessful applicants by the share of the transaction costs devoted to the preparatory phase of the application of the successful applicants, the percentage share of transaction costs of unsuccessful applicants would be 2.7% (OP E) and 3.5% (ECO ENERGY) of the average subsidy.

3.2. Administrative costs

Administrative costs are associated with the costs assigned for technical assistance in the programmes. It is assumed that the administrative costs are the same across all subsidised projects (all project get equal “attention” from the administrators of the subsidy). The levels of technical assistance for OP E and OPEI (ECO-ENERGY) are summed up in Table 2.

The numbers above are likely to represent the lower boundary of the administrative burden, as the technical assistance does not cover some of the stages of the administrative process, mostly the ones related to tasks that are carried out by other bodies than the main administrative body. For instance, for OP E, the main administrative body was the State Environmental Fund. However, the strategic issues were covered by the Ministry of the Environment and the financial flows between the European Commission and the administration body are channelled by the Ministry of Finance. The costs of these bodies are not covered in the technical assistance (but can be estimated to be an order of magnitude

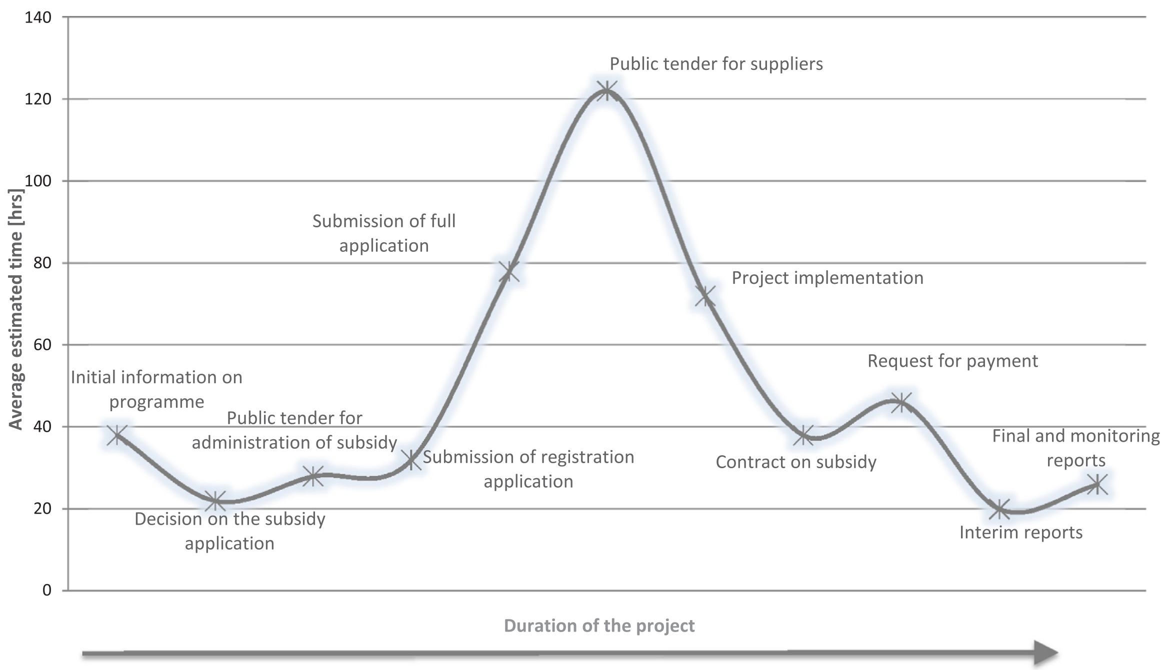

Fig. 2. Amount of time of individual phases of the administration process of the subsidy recipient – ECO-ENERGY.

Table 1
Transaction costs of subsidy recipients of OP E and ECO-ENERGY.

	Time (labour) costs [EUR]	External costs [EUR]	Average subsidy [EUR]	Relative transaction costs [%]
OP E	3,520	13,710	293,696	5.9
ECO-ENERGY	4,583	19,077	320,041	7.4

Note: The total labour costs in the respective economic activities were used to translate the estimated time into monetary terms (EUR 10.6 in the public sector and EUR 9.3 in industry in 2011 (Czech Statistical Office, 2012) The exchange rate of EUR/CZK 24.6 was used.

Table 2
Technical assistance.
Source: (Ministry of Industry and Trade, 2015; Ministry of the Environment, 2009), own calculations

Programme	Total allocation [EUR]	Technical assistance [% of total allocation]	Technical assistance [% of allocation on individual projects][a]
OP E	168,000,000	2.91%	2.99%
OPEI	105,000,000	2.93%	3.02%

[a] In case of OP E that means share of technical assistance on allocation for priority axis 1–7, in case of OPEI, share of technical assistance on allocation for priority axis 1–6.

smaller).

The interviews with the representatives of the administration bodies revealed that similarly to the experience of the applicants, the most time intensive is the evaluation of the project applications. Secondly, the administrators of the subsidy programmes identified the checking of public tenders carried out by the subsidy recipients as particularly demanding. The demanding character of the public tenders can be attributed to the legal framework. However, the time intensity is mainly attributed to the fact that administrators check the public tender dossiers before the launch of the public tender.

3.3. Factors influencing transaction costs

Firstly, Figs. 3 and 4 endorse the lognormal distribution of the sample. While the non-transformed distribution for subsidy has a declining character of a distribution of an exponential type, the logarithms of subsidy exhibits shape typical for a normal distribution.

Following the regression analysis, the regression equations can be therefore formulated as[6]:

$$\textbf{ECO-ENERGY:}\quad \ln(\boldsymbol{TC}) = \boldsymbol{2.95} + \underset{(1.03)^{***}}{} \boldsymbol{0.56}\,\ln(\boldsymbol{S})\underset{(0.09)^{***}}{}\qquad Adj.\ R^2 = 0.55$$

$$\textbf{OPE:}\quad \ln(\boldsymbol{TC}) = \boldsymbol{5.17} + \underset{(1.13)^{***}}{} \boldsymbol{0.36}\,\ln(\boldsymbol{S})\underset{(0.09)^{***}}{}\qquad Adj.\ R^2 = 0.20$$

The F-test for both regression equations is significant; therefore the model has explanatory power. The results suggest that there is a positive dependence of transaction costs on the size of the subsidy for both programmes. Both coefficients, $\boldsymbol{\alpha_1}$ and $\boldsymbol{\alpha_2}$, are significant. The coefficients α_1 and α_2 can be interpreted as elasticity, i.e. for ECO-ENERGY if subsidy changes by 10%, we could expect the transaction costs to change by 5,6%. The results further imply that the size of the subsidy could be a stronger predictor of transaction costs for OP E (0,56) than for ECO-ENERGY (0,36).

A regression equation was developed to test the two coefficients β_1 and β_2, and $\alpha_1$and α_2. This in turn gives an answer to the hypothesis that the transaction costs differ depending on the type of actor. The regression function is formulated as follows:

$$\ln(\boldsymbol{TC}) = \underset{(1.24)^{***}}{\boldsymbol{7.23}} - \underset{(1.87)}{\boldsymbol{2.87}\ \boldsymbol{D}} + \underset{(0.08)^{***}}{\boldsymbol{0.36}\ \ln(\boldsymbol{S})} + \underset{(0.13)}{\boldsymbol{0.20}\ \boldsymbol{D}\ \ln(\boldsymbol{S})}$$

Both coefficients of model difference (intercept and slope) are insignificant. The p-values both for coefficient (α_1 - α_2) and for coefficient (β_1 - β_2) are greater than 0.05 (and even greater than 0.1). That

[6] (Standard error) ***p = 0.01, **p = 0.05, *:p = 0.1. No * means that the coefficients are not statistically significant at conventional levels.

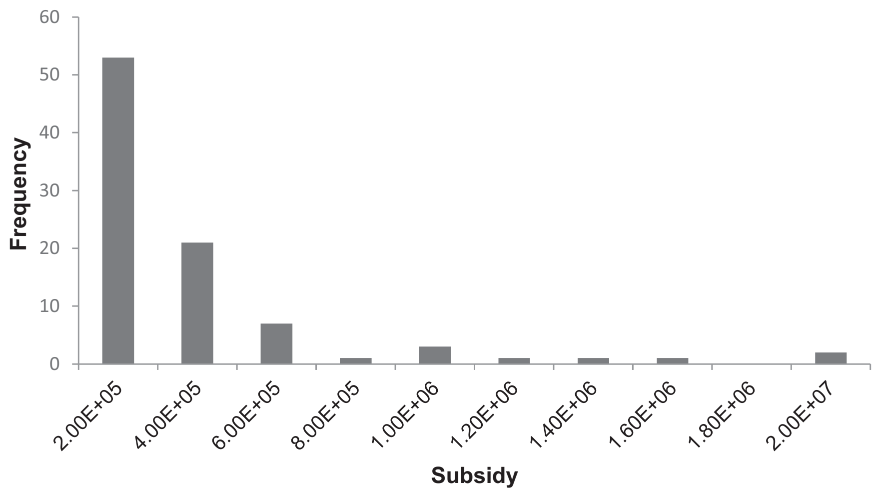

Fig. 3. Histogram of the size of the subsidy.

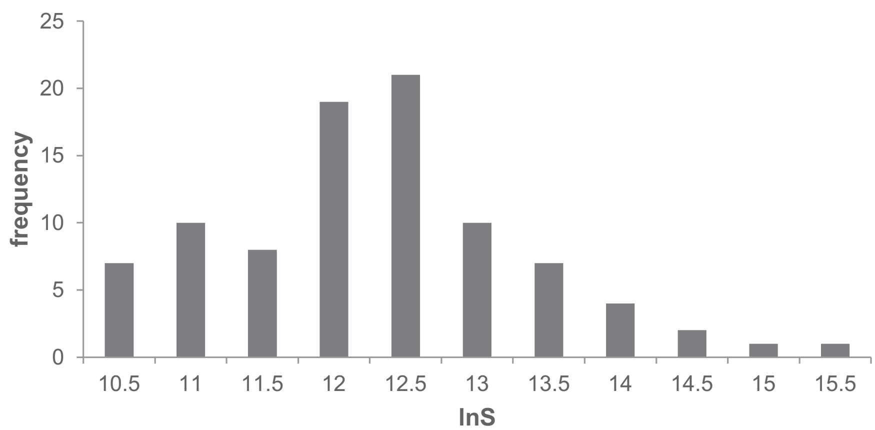

Fig. 4. Histogram of the natural logarithm of the size of the subsidy.

indicates that we cannot reject the null hypothesis and therefore cannot state that on the 95% (90%) confidence level the regression coefficient β_1 is significantly different from and β_2, or that $\alpha_1$is different from α_2. However, the joint F-test rejects equality of both slopes and intercepts. Based on additional test, we can say that the slope coefficients β are the same and the programmes differ in the intercept term. Therefore, based on the data sample, we cannot say that the slope of total transaction costs would be different depending on the type of the actor – i.e. that there would be a statistically significant difference between the "behaviour" of private companies and public entities, when it comes to transaction costs in energy efficiency programmes.

If the same analysis is performed for the two components of the transaction costs: the costs of time and costs of external services, the regression equations are:[7]

ECO−ENERGY	***OP E***
$\ln(\boldsymbol{C_E}) = \boldsymbol{0.74}\ \ln(\boldsymbol{S})$	$\ln(\boldsymbol{C_E}) = \boldsymbol{4.52} + \boldsymbol{0.38}\ \ln(\boldsymbol{S})$
(0.12)***	(1.68)***(0.14)***
$Adj.\ R^2 = 0.52$	$Adj.\ R^2 = 0.13$
$\ln(\boldsymbol{C_T}) = \boldsymbol{5.45} + \boldsymbol{0.24}\ \ln(S)$	$\ln(\boldsymbol{C_T}) = \boldsymbol{5.34} + \boldsymbol{0.22}\ \ln(S)$
(0.98)***(0.08)***	(0.89)***(0.07)***
$Adj.\ R^2 = 0.20$	$Adj.\ R^2 = 0.15$

Analogically to the analysis with total transaction costs, a regression equation was formulated to test the two coefficients β_1 and β_2, and $\alpha_1$and α_2 in case of independent variable external costs and time costs. The regression function for the external services has been estimated with results as follows:

$$\ln(\boldsymbol{C_E}) = \boldsymbol{4.52} - \boldsymbol{4.18}\ \boldsymbol{D} + \boldsymbol{0.38}\ \ln(\boldsymbol{S}) + \boldsymbol{0.36}\ \ln(\boldsymbol{S})\ \boldsymbol{D}$$

(1.63)***(2.24)* (0.13)*** (0.19)*

$$\ln(\boldsymbol{C_T}) = \boldsymbol{5.34} + \boldsymbol{0.11}\ \boldsymbol{D} + \boldsymbol{0.22}\ \ln(\boldsymbol{S}) + \boldsymbol{0.01}\ \ln(\boldsymbol{S})\ \boldsymbol{D}$$

(0.95)***(1.31) (0.08)*** (0.01)

For the variable of costs for external services, there is a statistically significant difference (on 90% confidence level) between the two programmes, suggesting that there is a difference in how the two actors handle tendering for external services for administration of the subsidies. Conversely, the results suggest that the costs of time for the two programmes are not statistically different from each other – as can also be inferred directly from the regression equation.

[7] The constant is not statistically significant on any conventional level, therefore has been excluded in this case.

Table 3
Transaction costs of OP E and ECO-ENERGY.

Programme	Transaction costs of successful applicants [%]	(Estimated) transaction costs of unsuccessful applicants [%]	Administrative costs [%]
OP E	5.9%	2.7%	3%
ECO-ENERGY	7.4%	3.5%	3%

4. Discussion

4.1. The level of transaction costs

The percentage share of transaction costs of the analysed energy efficiency subsidy programmes is summarised in Table 3. The results are indicative given the size of the sample (90 respondents).

The time lag between the implementation of the subsidy and the research may have influenced the results. The transaction costs were estimated through a combination of interviews and a questionnaire survey. The respondents estimated the time spent on individual stages of the subsidy administration process and also the external costs. They were selected from the applicants who went through the whole administration process. This, however, meant that the time lag between the actual project and the survey was quite significant (usually 1–3 years). Clearly, the higher the time lag, the more difficult to correctly estimate the transaction costs (see also McCann et al., 2005).

Transaction costs rise for third-party actors in the given programme, too. These can be for instance the suppliers of the subsidised energy efficiency measures, which may need to acquire specific certification to be eligible as suppliers in the programme, or banks that cooperate with the programme. In the analysed programmes, the third parties were included only as the external companies supporting the applicants in the administration process. In this case, it can be assumed that all costs connected with the programme are reflected in the price of the service.

To correctly estimate the structure and level of transaction costs, the unsuccessful applicants should be covered in the analysis (Björkqvist and Wene, 1993). For OP E the success rate of the applications is 53%, and in ECO-ENERGY it is 69%. However, for both programmes, only data on successful applicants are publicly available. Therefore, the transaction costs of unsuccessful applicants could not be properly analysed. That means that a significant part of the transaction costs cannot be thoroughly analysed. The important message is not to omit this significant segment of actors, both in ex-ante and ex-post evaluation of the policy instruments. Relatedly, ex-ante and ex-post evaluation of the programme should aim at covering the actors/entities that decided to implement the measures without the subsidy programme.

To properly analyse administrative costs, it is crucial to detect the institutions or bodies that are responsible for the operation of the programme and set the boundary of the whole system. For the programmes analysed in this article, the boundary is the Czech Republic. However, given the fact that the programmes are financed from European funds, the national-European negotiations, administrative procedures and financial flows should be taken into account as well.

In this study the effect of the learning curve appears weaker than in other research studies (e.g. Falconer and Whitby, 2000; Kiss, 2016; Lee and Han, 2016; Michaelowa et al., 2003; Michaelowa and Jotzo, 2005). Even though the statistical analysis was carried out for applicants with one project only, there were a high number of respondents with more than one project (i.e. they applied with various projects at once or applied subsequently within different calls). The in-depth interviews revealed that, especially in the case of towns and cities, this does not necessarily mean that the transaction costs for these applicants would be lower. In the case of the public administration, if the respondents applied for more projects in the same programme, the various projects tend to fall under different departments (e.g. renovation of a school under the Department of Education, healthcare centre renovation under the Department of Public Health). The different parts of the administration hardly communicate and therefore do not make use of the potential for the transfer of knowledge and advantages of a learning curve. The second reason is the below further mentioned fluctuation of political employees.

4.2. The factors of project size and actors

Various studies have identified the relationship between the size of the project (or the performance) and the level of transaction costs (Bakam et al., 2012; Michaelowa and Jotzo, 2005; Mundaca et al., 2013). The data from the two analysed programmes, OP E and ECO-ENERGY has confirmed this premise. The relation is logarithmic, i.e. it seems that for bigger projects, the burden of transaction costs will be lower than for smaller projects. Following the regression function (for ECO-ENERGY), if the subsidy is EUR 10,000, the burden of transaction costs would be over 30%, for the subsidy of EUR 100,000, it would be 12%, and for EUR 1,000,000, it would be only 4%. The same pattern can be observed for OP E with the burden of transaction costs of 48% for the subsidy of EUR 10,000 going down to 2% for a subsidy of EUR 1,000,000. Therefore, in line with, e.g. (Michaelowa and Jotzo, 2005) economies of scale apply in the case of the analysed energy efficiency programmes. That would also suggest that the fixed costs (unrelated to the size of the project) prevail over variable costs.

On the other hand, the hypothesis that the size of transaction costs differs according to the type of actor in the energy efficiency programmes could not be confirmed. The analysis has shown that there is not a statistically significant difference between the two subsets of data, which differ only by the type of applicant. Yet, the results are close to conventional 10% confidence levels ($p = 0.13$ for (α_1 - α_2) and 0.11 for (β_1 - β_2)).[8]

However, taking a closer look at the data, it can be seen that while there is no statistical difference between the costs of time and the size of the project between the two types of applicants, there is an observable difference as to the size of costs of external services. While the difference is on the verge of statistical significance (being significant only at 90% confidence level), the results suggest that private companies may be able to negotiate the services more effectively, but only for projects up until a certain size. The intercept of the two regression equations is at roughly EUR 300,000 subsidy, which includes 75% of the sample projects. The results seem to imply that unlike public entities, private companies in these programmes tend to contract suppliers of external services specifically for the project and therefore the amount of external services is in a tighter relationship with the size of the project. One can further speculate that the public entities will have the procedures and contracts standardised and therefore less dependent on the actual size of the contract.

On the other hand, for both OP E and ECO-ENERGY subsidy recipients the internal (time) costs were much less correlated with the size of the project – both slopes are low – 0.2. That would suggest that the activities carried out internally are predominantly of a fixed nature (for example, disregarding the size of the project, the structure and complexity of project applications remain the same). The results, therefore, suggest that there is room for optimisation for both public and private entities.

As for the structure of transaction costs, the main source of transaction costs for both types of applicants and administration bodies in the analysed programmes lies in the preparation process (the search for information, internal approval procedure and application submission)

[8] If the same analysis were performed for normal distribution of the sample – i.e. without converting the two variables into logarithms, there would be a statistically significant difference between the two programmes. That means that such hypothetical difference would be primarily pulled by large projects in the sample, which, however, do not form the core of the sample, nor of the population.

and the processes connected with public tenders for implementation of the energy efficiency measures.

The transaction costs related to tender procedures were found to be largely dependent both on existing legislation and on internal conditions set by the programmes. A straightforward and simple legal environment could play a significant role in decreasing the transaction costs burden (McCann, 2013). However, the respective transaction costs cannot be attributed only to this external factor. For OP E the programme conditions were set in a way that the initiation of public tenders was dependent upon approval from the administration body. Therefore, long time delays often developed, making the realisation of the energy efficiency measures more difficult (e.g. building envelope reconstruction in schools needs to fall in the time of summer holidays not to interfere with the school year). For ECO-ENERGY, the requirement to call for a public tender for energy efficiency measures stems purely from the conditions of the programme. In both programmes, the administrators aimed to streamline the procedures by developing checklists and standard documents.

Also, the type of actors seems to play a role in the very research on transaction costs. Given the nature of the subsidy recipients in OP E (towns, municipalities), the political cycle is a limiting factor. Often, the people responsible for the administration process have been replaced in the meantime (typically the mayors of the small villages), that means that the data on the transaction costs is irreversibly lost. The situation could be partially solved if the applicants had a tracking system in place, in which they assigned their time directly to a particular project. This problem did not arise in the case of ECO-ENERGY; continuity in the private companies systems seemed to be therefore better secured.

5. Conclusions and policy implications

Operational programmes distribute a significant amount of financing; large part is devoted to energy efficiency. For instance in the Czech Republic, over 1 billion EUR was dedicated specifically to energy efficiency measures solely in the programming period 2007 – 2013, so about 5% of the total allocation. However, monitoring and evaluation of the programmes remain often inadequate. It has been shown that when designing energy efficiency (subsidy) programmes transaction costs should be included in the ex-ante evaluations. Furthermore, ex-post evaluation of the programmes needs to cover not only the effects of the programme (energy efficiency gains, and other), but also total costs of the programme, including transaction costs.

The data in this study suggests that the transaction costs in energy efficiency subsidy programmes are of non-negligible levels, altogether averaging at 11%–14% of the total subsidy allocation. The results are comparable in their order of magnitude to the conclusions of available international analyses (even though due to methodological differences the studies tend to be rather case specific). In line with other studies, the size of transaction costs is closely related to the size of the project. For smaller projects, there seems to be directly proportionate relation whereas for bigger projects economies of scale apply and the total burden of transaction costs decreases.

Other factors being the same, the type of actor did not show to play the major role in the size of transaction costs in the two studied programmes. However, some differences can be traced in how the two actors negotiate for external services for implementing the projects. For smaller projects, which form most of the sample and the whole population in the programme, private companies are more effective, while for bigger projects (over EUR 300,000) public entities seemed more efficient. For both types of actors, transaction costs mostly arise in the preparatory phase of the application and tender procedures.

In order to optimise transaction costs, policymakers should try to address both the internal and external factors in programme preparation. Regarding the internal factors, a clear setting of the conditions of the programmes, provision of templates and streamlining of processes seem to be the most powerful tools. Externally, the legal environment determines to a high extent the complexity of the tendering process.

The data further revealed that there is room for improvement in setting the administrative processes for public bodies as recipients in energy efficiency subsidy programmes. Specifically, the public bodies may reconsider setting up their public tendering procedures to reflect the actual size of the project better.

Even though it was not the primary goal of the paper, the research also demonstrated that unsuccessful applicants need to be taken into account both in the ex-ante and ex-post evaluation of the programmes. The transaction costs born by unsuccessful applicants represent a non-negligible share of the subsidy and should not be omitted. (In extreme cases, transaction costs may event prevent possible applicants from applying.) A two-stage submission process may be a good way to lower the transaction costs for the unsuccessful applicants.

The research has opened further questions that could be examined, such as whether the role of actors in transaction costs is country/region specific or to what extent transaction costs develop over time in similar programmes. Systemic evaluation of transaction costs in policy measures could give answers to those questions.

Acknowledgements

We would like to thank all the respondents of the survey for their time and helpfulness. The data collection was supported by the Programme EFEKT - the state programme in support of energy saving and utilisation of RES of the Ministry of Industry and Trade of the Czech Republic. Data analysis and writing up of the article was supported by the research grant No. GA18-02756S provided by the Czech Science Foundation.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.enpol.2018.04.055.

References

Ahonen, H.-M., Hämekoski, K., 2005. Transaction Costs Under the Finnish CDM/JI Pilot Programme (No. Discussion paper No. 12). University of Helsinki, Helsinki.

Applica, Ismeri Europa, 2016. Ex post evaluation of Cohesion Policy programmes 2007–2013, focusing on the European Regional Development Fund (ERDF) and the Cohesion Fund (CF). WP1: Synthesis report (Report for the European Commission).

Bakam, I., Balana, B.B., Matthews, R., 2012. Cost-effectiveness analysis of policy instruments for greenhouse gas emission mitigation in the agricultural sector. J. Environ. Manag. 112, 33–44. http://dx.doi.org/10.1016/j.jenvman.2012.07.001.

Björkqvist, O., Wene, C.-O., 1993. A study of the transaction costs for energy investments in the residential sector, In: Proceedings of the 1993 Summer Study. The European Council for an Energy Efficient Economy (ECEEE), Stockholm, pp. 23–30.

Cheung, S.N.S., 1998. The transaction costs Paradigm 1998 presidential address Western Economic Association. Econ. Inq. 36, 514–521. http://dx.doi.org/10.1111/j.1465-7295.1998.tb01733.x.

Coggan, A., Buitelaar, E., Whitten, S., Bennett, J., 2013. Factors that influence transaction costs in development offsets: who bears what and why? Ecol. Econ. Trans. Costs Environ. Policy 88, 222–231. http://dx.doi.org/10.1016/j.ecolecon.2012.12.007.

Coggan, A., Whitten, S.M., Bennett, J., 2010. Influences of transaction costs in environmental policy. Ecol. Econ. 69, 1777–1784. http://dx.doi.org/10.1016/j.ecolecon.2010.04.015.

Creswell, J.W., Plano Clark, V.L., 2011. In: SAGE Publications Inc (Ed.), Designing and Conducting Mixed Methods Research, 2nd edition. SAGE Publications.

Czech Statistical Office, 2012. Labour Costs - 2011.

European Commission, 2010. Communication from the commission Europe 2020. A strategy for smart, sustainable and inclusive growth (No. COM(2010) 2020 final).

European Parliament and Council, 2012. Directive 2012/27/EU of the European parliament and of the council of 25 October 2012 on energy efficiency, amending directives 2009/125/EC and 2010/30/EU and repealing directives 2004/8/EC and 2006/32/EC. Off. J. Eur. Union.

Falconer, K., Whitby, M., 2000. Untangling red tape: scheme administration and the invisible costs of European agri-environmental policy. Eur. Environ. 10, 193–203. http://dx.doi.org/10.1002/1099-0976(200007/08)10:4<193::AID-EET231>3.0.CO;2-D.

Galvin, R., 2015. How many interviews are enough? Do qualitative interviews in building energy consumption research produce reliable knowledge? J. Build. Eng. 1, 2–12. http://dx.doi.org/10.1016/j.jobe.2014.12.001.

Gu, B., Hitt, L.M., 2001. Transaction costs and market efficiency, In: ICIS 2001

Proceedings. Presented at the Twenty-Second International Conference on Information Systems, Association for Information Systems.
Hein, L.G., Block, K., 1995. Transaction costs of energy efficiency improvement, In: Proceedings of the ECEEE 1995 Summer Study. The European Council for an Energy Efficient Economy (ECEEE), Stockholm.
Jaraité, J., Convery, F., Di Maria, C., 2010. Transaction costs for firms in the EUETS: lessons from Ireland. Clim. Policy 10, 190–215. http://dx.doi.org/10.3763/cpol.2009.0659.
Kiss, B., 2016. Exploring transaction costs in passive house-oriented retrofitting. J. Clean. Prod. Adv. Sustain. Solut.: Interdiscip. Collab. Res. Agenda 123, 65–76. http://dx.doi.org/10.1016/j.jclepro.2015.09.035.
Lee, K., Han, T.-W., 2016. How vulnerable is the emissions market to transaction costs?: an ABMS Approach. Energy Policy 90, 273–286. http://dx.doi.org/10.1016/j.enpol.2015.12.013.
Lizal, L., Singer, M., Baghdasarian, A., 2001. An estimation of Euler's equation of a profit maximizing firm. In: Liuhto, K. (Ed.), Ten Years of Economic Transformation. Lappeenranta University of Technology, pp. 126–142.
Matthews, R.C.O., 1986. The economics of institutions and the sources of growth. Econ. J. 96, 903–918. http://dx.doi.org/10.2307/2233164.
McCann, L., 2013. Transaction costs and environmental policy design. Ecol. Econ. Trans. Costs Environ. Policy 88, 253–262. http://dx.doi.org/10.1016/j.ecolecon.2012.12.012.
McCann, L., Colby, B., Easter, K.W., Kasterine, A., Kuperan, K.V., 2005. Transaction cost measurement for evaluating environmental policies. Ecol. Econ. 52, 527–542. http://dx.doi.org/10.1016/j.ecolecon.2004.08.002.
Michaelowa, A., Jotzo, F., 2005. Transaction costs, institutional rigidities and the size of the clean development mechanism. Energy Policy 33, 511–523. http://dx.doi.org/10.1016/j.enpol.2003.08.016.
Michaelowa, A., Stronzik, M., Eckermann, F., Hunt, A., 2003. Transaction costs of the Kyoto Mechanisms. Clim. Policy 3, 261–278. http://dx.doi.org/10.1016/S1469-3062(03)00061-5.
Ministry of the Environment, 2009. The Operational Programme Environment for the Period 2007–2013.
Ministry of Industry and Trade, 2015. The Operational Programme Enterprise and Innovation.
Mundaca, L., 2007a. Transaction costs of Tradable White Certificate schemes: the Energy Efficiency Commitment as case study. Energy Policy 35, 4340–4354. http://dx.doi.org/10.1016/j.enpol.2007.02.029.
Mundaca, L., 2007b. Transaction costs of energy efficiency policy instruments. In: Attali, S., Tillerson, K. (Eds.), ECEEE Summer Study. Presented at the ECEEE Summer Study. European Council for an Energy Efficient Economy, pp. 281–291.
Mundaca, L.T., Mansoz, M., Neij, L., Timilsina, G.R., 2013. Transaction costs analysis of low-carbon technologies. Clim. Policy 13, 490–513. http://dx.doi.org/10.1080/14693062.2013.781452.
Musole, M., 2009. Property rights, transaction costs and institutional change: conceptual framework and literature review. Prog. Plan. Prop. Rights Trans. Costs Inst. Chang.: Concept. Framew. Lit. Rev. 71, 43–85. http://dx.doi.org/10.1016/j.progress.2008.09.002.
North, D.C., 1990. Institutions, Institutional Change and Economic Performance. Cambridge University Press.
Ofei-Mensah, A., Bennett, J., 2013. Transaction costs of alternative greenhouse gas policies in the Australian transport energy sector. Ecol. Econ. Trans. Costs Environ. Policy 88, 214–221. http://dx.doi.org/10.1016/j.ecolecon.2012.12.009.
Ostertag, K., 1999. Transaction Costs of Raising Energy Efficiency. Presented at the The IEA International Workshop on Technologies to Reduce Greenhouse Gas Emissions: Engineering-Economic Analyses of Conserved Energy and Carbon, Washington D.C., USA.
Prušvic, D., 2006. Porovnání výběru pojistného a daní [Comparison of tax and insurance collection]. VUPSV, Praha.
Ramboll, M.C.A., Institute for European Environmental Policy, 2016. Energy efficiency in public and residential buildings Final Report. Work Package 8. Ex post evaluation of Cohesion Policy programmes 2007-2013, focusing on the European Regional Development Fund (ERDF) and the Cohesion Fund (CF). Publications Office of the European Union, Luxembourg.
Rao, P.K., 2003. The Economics of Transaction Costs. Palgrave Macmillan, Hampshire and New York.
Reddy, A.K.N., 1991. Barriers to improvements in energy efficiency. Energy Policy Clim. Change – Ctry. Case Stud. 19, 953–961. http://dx.doi.org/10.1016/0301-4215(91)90115-5.
Sanstad, A.H., Howarth, R.B., 1994. “Normal” markets, market imperfections and energy efficiency. Energy Policy Mark. Energy Effic. 22, 811–818. http://dx.doi.org/10.1016/0301-4215(94)90139-2.
Sathaye, J., Murtishaw, S., 2004. Market Failures, Consumer Preferences, and Transaction Costs in Energy Efficiency Purchase Decisions (No. LBNL-57318). Lawrence Berkeley National Laboratory.
Schleich, J., Gruber, E., 2008. Beyond case studies: barriers to energy efficiency in commerce and the services sector. Energy Econ. 30, 449–464. http://dx.doi.org/10.1016/j.eneco.2006.08.004.
SEVEn, 2010. Czech Republic: Overview of the mechanisms of Structural and Cohesion Funds. (Country report of the PromoSCene project).
Shahab, S., Clinch, J.P., O'Neill, E., 2018. Accounting for transaction costs in planning policy evaluation. Land Use Policy 70, 263–272. http://dx.doi.org/10.1016/j.landusepol.2017.09.028.
Valentová, M., 2013. Transakční Náklady Programů na podporu energetické efektivnosti [Transaction costs of energy efficiency subsidy programmes]. Czech Technical University in Prague, Prague.

ANNEX 5

'Evaluation of the GreenBuilding Programme' *(Valentová and Bertoldi 2011)*

Energy and Buildings 43 (2011) 1875–1883

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Evaluation of the GreenBuilding Programme

Michaela Valentová [a,*], Paolo Bertoldi [b]

[a] Czech Technical University in Prague, Technická 2, 166 27 Praha 6, Czech Republic
[b] European Commission, DG JRC, Institute for Energy, Renewable Energy Unit, TP450, 21020 Ispra, Italy

ARTICLE INFO

Article history:
Received 28 June 2010
Received in revised form 29 January 2011
Accepted 23 March 2011

Keywords:
Energy efficiency in buildings
GreenBuilding Programme
Voluntary programme evaluation
European Union

ABSTRACT

In early 2006 the European Commission launched the GreenBuilding Programme (GBP), aimed at improving the energy efficiency of existing as well as newly constructed non-residential buildings in Europe on a voluntary basis. Building owners from different sectors are participating in the programme, e.g., public authorities with schools, hospitals or swimming pools, companies from the services and industry sectors with office buildings, sports centres and hotels. The aim of the paper is to provide a summary analysis of the results of the GBP over its almost four-year operation – from the launch of the programme in 2006 until the end of 2009.

By the end of 2009, 167 Partners had joined the programme with almost 300 buildings from all sorts of fields and sectors of operation. The total savings achieved by the Partners are 304 GWh/year. The buildings themselves may vary in age, size and use, but they all have in common the energy performance, which goes far beyond the average performance of buildings in the participating countries. The paper focuses on efficiency measures implemented in the participating buildings and the achieved energy savings.

1. Introduction: the GreenBuilding Programme

In its 2006 Action Plan on Energy Efficiency [1], the European Commission (EC) identified the building sector as an area where important improvements in energy efficiency could be realised. According to the Action Plan, the building sector accounts for more than 40% of the final energy demand in Europe. At the same time, improved heating and cooling of buildings constitutes one of the largest potentials for energy savings and thus reduction of CO_2 emissions. Such savings would also improve the energy supply security and the EU's competitiveness, while creating jobs and raising the quality of life in buildings.

In early 2006, the European Commission initiated the GreenBuilding Programme (GBP). This programme aims at improving the energy efficiency and expanding the integration of renewable energies in non-residential buildings in Europe on a voluntary basis. The programme encourages owners of non-residential buildings to implement cost-effective measures which enhance the energy efficiency of their buildings in one or more equipment systems. The GBP is complementary to the EU Energy Performance of Buildings Directive (EPBD) as it stimulates additional savings in the non-residential building sector.

To become a GBP partner, building owners perform an energy audit of their existing buildings and formulate an action plan to improve energy efficiency. By applying to the GBP, potential Partners agree to reduce the primary energy demand of the building by at least 25% (if economically viable) and to report the results of the renovation measures. The energy consumption is measured prior to and after the renovation. For new construction, investors or building owners design a building using at least 25% less energy than requested by the building code in force at the time. The energy savings are calculated from modelled energy use.

Fourteen organisations from 13 European countries are supporting the implementation of the GBP in the national context; these organisations are called National Contact Points (NCP) and they assist building owners in this process by providing guidelines for energy saving renovation and a website in the national language containing an inventory of best-practices. Other private and public organisations (Endorsers) may help potential Partners join the programme. Besides reducing energy as well as operational costs, other reasons for building owners to join GBP are

- Public recognition for the participating organisations
- Practical help from the NCP
- Public commitment to environmentally friendly behaviour
- Corporate Social Responsibility
- Reduction of CO_2-emissions

Participation in the GBP for existing buildings starts with the submission of an action plan defining the scope and nature of the

* Corresponding author. Tel.: +420 22435 3308; fax: +420 23333 4232.
E-mail addresses: michaela.valentova@fel.cvut.cz (M. Valentová), paolo.bertoldi@ec.europa.eu (P. Bertoldi).

0378-7788/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.enbuild.2011.03.028

Table 1
Building type.

Commercial Centre	Buildings containing shops, restaurants, conference rooms, offices, etc.
Education	From kindergartens to universities
Healthcare	Hospitals, and also rehabilitation, day care centres, etc.
Industry	Warehouses, storage, production halls, manufacturing buildings, workshops (there can also be offices, but these do not represent the main part of the building)
Office	Buildings mainly for office use
Leisure	Spas, leisure centres, swimming pools
Public administration	Municipal halls, courts, penitentiaries
Retail	Supermarkets, shops
Other	Churches, canteens, community centres, social housing, social care, airports, train stations

company's commitment. Based on an initial energy audit, the action plan must define the buildings in which energy efficiency measures will be undertaken as well as the energy services (heating, lighting, water heating, ventilation, air-conditioning, office equipment, etc.) and the specific measures to which the commitment applies. If the action plan is accepted by GreenBuilding, the company is granted Partner status. For new buildings, energy modelling and a description of the building are needed to prove that the building's energy consumption is 25% below that specified in the building code. The GBP encourages its Partners to tap a large reservoir of profitable investments without the need for specific incentives from the public authorities. GBP investments use proven technology, products and services for which efficiency has been demonstrated. It is thereby considered to make good business sense for companies to join the GBP [2].

GreenBuilding provides support to the Partners in the form of information resources and public recognition, such as media coverage in newspapers and magazines, presentation at fairs and conferences throughout Europe, a regular newsletter, and a brochure and a catalogue of success stories. The GBP plaque allows Partners to show their responsible entrepreneurship to their clients.

The present paper analyses the results of the GreenBuilding Programme achieved so far. It focuses on the energy savings achieved and the energy efficiency measures implemented in the participating buildings.

2. Methods

Partners whose buildings join the GreenBuilding Programme attach a report in their application in which they provide information on the level of achieved savings and a description of the energy efficiency measures through which they achieved the declared savings. These reports served as a basis for the analysis. The period under assessment is from 2006 to 2009.

The buildings are assessed as to the reported year of construction (and in this connection, whether the buildings are new or refurbished), floor area and prevalent use (building type). As there are many types of buildings, the following table (Table 1) shows the main categories into which the buildings are categorised in order to allow for the analysis while capturing the prevalent uses of the building.

The achieved energy savings are analysed as to their absolute levels (MWh/year) and in relative terms (% of the consumption). The achieved (or modelled) energy consumption is compared to the pre-refurbishment state for existing buildings or to the relevant legal requirements or conventional buildings for new buildings. The general characteristics of the buildings (building type and area, year of construction, country) are also taken into account.

The efficiency measures vary to a certain extent among Partners (given the different use, geographical area or year of construction). Nevertheless, based on the Partners' reports, the measures are categorised into seven main areas which have been found to be the common denominator (Table 2).

The main categories (heating, ventilation/air-conditioning, building envelope, lighting, renewable energy sources (RES), control systems and other) are in some cases further divided into subcategories to give a better picture of the measures applied. Within the general category of heating, combined heat and power generation (CHP), heat pumps and biomass boilers are earmarked (the last two could at the same time be categorised under RES). RES are further divided into solar panels and photovoltaic installations. From building envelope measures, summer heat protection is highlighted. The category "Other" mostly includes water saving systems, as well as efficient appliances or staff training.

All the data analysed in the paper is submitted by the Partners. There are some missing pieces of information in the Partner reports. Nevertheless, the missing items of information are relatively negligible – there are only two buildings for which no report has been provided. Yet, as there is no common format of the reporting form in the participating countries, for some Partners only partial information is provided. The only section, however, where the number of provided sets of data is significantly lower is the information on economic characteristics of the projects, in which the sample consists of only 22 Partners.

The analysis is based on Partners' information, which undergoes a double quality and consistency check. The reporting forms and data provided by the Partners are always checked by the National Contact Points for inconsistencies before being sent to the Joint Research Centre (JRC). The JRC reviews the reports too before granting the building and the organisation the status of GreenBuilding Partner. Nevertheless, the analysed data should be taken keeping this limitation in mind.

3. Results of the GreenBuilding Programme

3.1. Number and type of participating buildings

As at the end of December 2009, the total number of GBP Partners had reached 167. The total number of GBP certified buildings

Table 2
Types of measures.

Category	Subcategory
Heating	Reconstruction of heating system
	CHP
	Heat pumps
	Biomass boilers
Ventilation/Air-conditioning	Ventilation/Air-conditioning
Building envelope	Building envelope
	Summer heat protection
Lighting	Lighting
Renewable Energy Sources (RES)	Photovoltaic (PV) panels
	Solar panels
Control Systems	Control systems
Other	Other

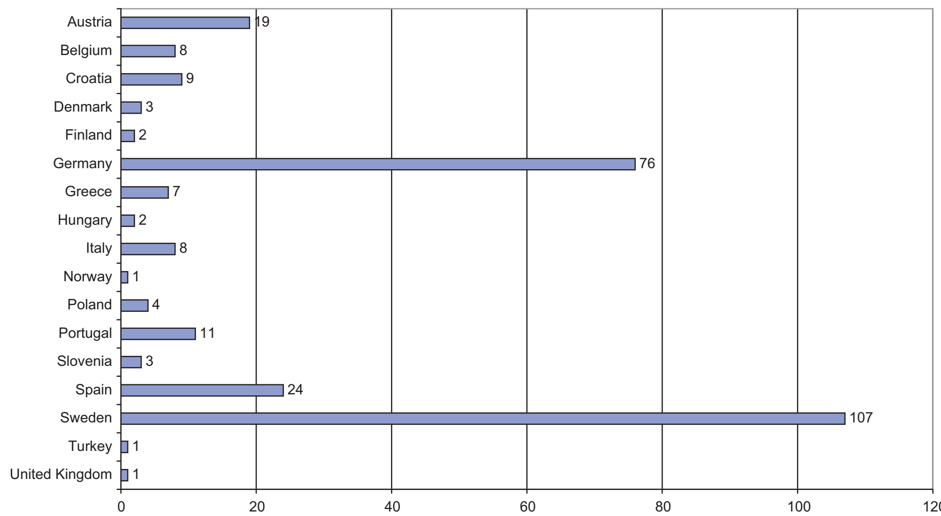

Fig. 1. Buildings per country.

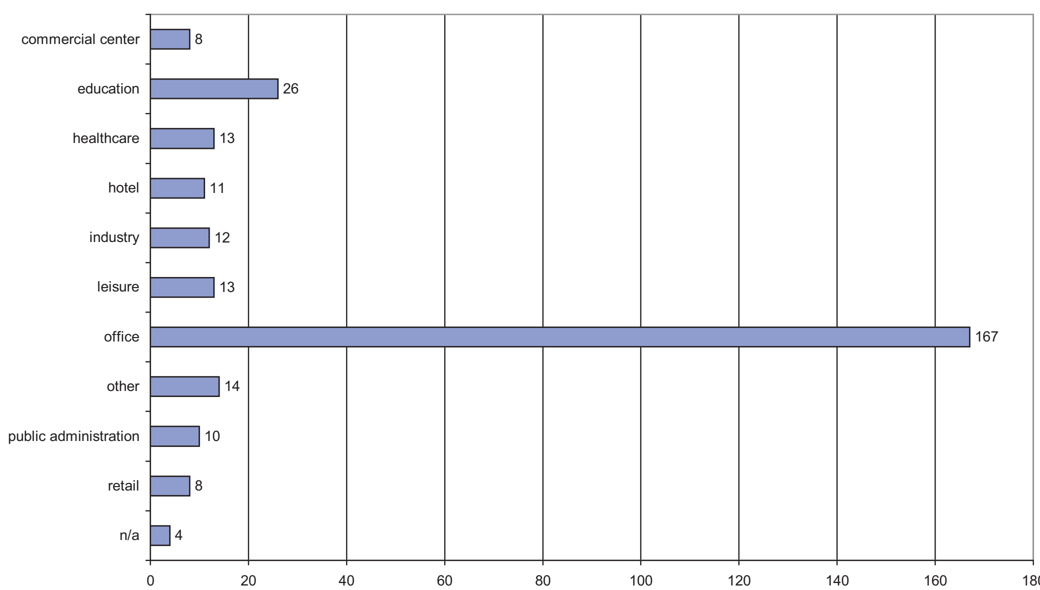

Fig. 2. Building type.

was 286.[1] During the first two and a half years of operation of the Programme (2006 – mid 2008), 71 Partners joined with 87 Buildings [3]. Since then, the number of Partners had more than doubled and the number of Buildings more than tripled. The Partners come from 17 countries, of which 14 are EU member states. Geographically, both southern and northern countries are represented. The highest number of GBP Partners come from Germany (48), followed by Sweden (36). Austria has 18 Partners and Spain 14. From non-EU countries, there is one Partner from both Norway and Turkey, while there are nine Partners from Croatia. A few international companies, such as NCC Development, Skanska and Siemens, have joined the GBP in different countries.

The highest number of buildings has been registered in Sweden (107), with more than three buildings per Partner on average, followed by Germany with 76 buildings (i.e., approx. 1.5 building per Partner on average). In most countries though, the number of buildings to large extent reflects the number of Partners (Fig. 1).

Almost 60% (167 out of 286) of the Partner buildings are offices (Fig. 2). The second largest group of buildings is education buildings (8.8% of the GBP buildings). These include kindergartens, primary schools, high schools and universities. The public administration buildings (10 in total) comprise municipal houses as well as courts and penitentiaries. Healthcare, hotels, industry and leisure centres are all represented by 13 buildings (approx. 4% of total number of Partner buildings). Among other buildings, there are, for example, a church, a technology centre, a research institute, a canteen, libraries, a train station and social care and social housing centres. Two airports also joined the GBP. One is included in the category of office buildings because an office building belonging to the air-

[1] The GBP Certificate is always granted to a specific building. Therefore, one GBP Partner can join the Programme with more than one building. Each of these buildings is assessed separately and receives the certificate on an individual basis.

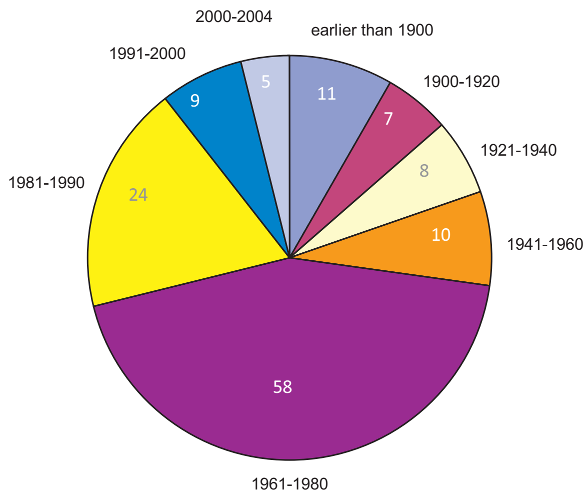

Fig. 3. Number of existing buildings according to the year of construction.

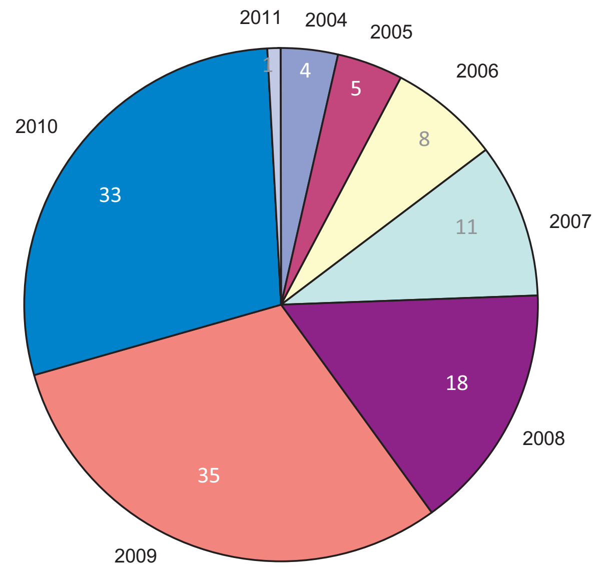

Fig. 4. Number of new buildings according to the year of construction.

port was constructed. The second is included in "Other" buildings because the buildings that were refurbished (satellite buildings or ramp services) are a specific building type.

The majority of the buildings belong to private organisations (77%), only 23% of the Partner buildings are public. All of the education facilities and, obviously, the public administration buildings in the GBP are run by public organisations. In healthcare facilities, there are both public and private organisations involved. The same applies to leisure centres (public are, for instance, municipal spas) or offices. On the other hand, commercial centres, hotels and industry buildings in the GBP are operated purely by private organisations.

The average area of the Partner buildings was more than 15,595 m^2.[2] However, the median of the sample is nearly half of the average – 8957 m^2 – meaning that 50% of the buildings are actually smaller than 9000 m^2. The sample is to a large extent skewed by commercial centres, which have the highest average floor area – more than 52,000 m^2. The smallest building only has 414 m^2; it is a historical building built in 1900 used as an office building of a regional association, with the primary energy savings reaching 455 MWh/year. The largest building of the GreenBuilding programme has 200,000 m^2 and is one of the new commercial centres, built in 2009, with savings compared to the building code in force of 7329 MWh/year.

Out of 285 buildings (for one building this information was not available), there are 126 new buildings and 159 existing, refurbished buildings. Among hotels, office buildings, public administration buildings and education facilities, refurbished buildings prevail – there are around twice as many existing buildings as new buildings. Conversely, there are far more registered new commercial centres, industry buildings and leisure facilities.

Most of the existing buildings were built between 1961 and 1980. The oldest building of the GBP was constructed in 1600. Another ten buildings were built before 1900 (Fig. 3), while the newest refurbished building was constructed in 2004.[3] The new buildings were constructed between 2004 and 2011 (Fig. 4). This means that the new buildings almost overlap with the existing, already refurbished buildings, and at the same time, some buildings are still under construction. In absolute terms, most of the Partner buildings were finished in 2009 (35 Partner buildings out of 247 where this information was available), followed by constructions finished in 2010 (33 Partner buildings) and in 2008 (18 Partner buildings).

[2] This is the net floor area. In 19 cases the net floor area was not reported, thus the gross floor area was used instead.

[3] It must be noted though that these are the years of original construction. In many cases, the buildings were of course reconstructed several times, or some parts of the buildings were added. This was however disregarded in the present analysis.

3.2. Energy savings

The GBP Partners usually report their savings in two ways: either as absolute annual savings or as kWh per m^2 and year. In some case, both sets of data are reported. In the case of relative savings (%), it is not important which method of reporting is used. However, if we are to analyse the absolute savings, in the case of the latter method (reporting kWh/m^2 y) recalculation is necessary.

Total savings of the GBP to date (GBP Partners until the end of 2009) have amounted to 304 GWh/year. The savings may have been underestimated. There are two reasons for this. Firstly, these savings have often been only estimated savings (e.g., for new buildings). And, as reported by some Partners, the verified savings tend to be even higher than the calculated levels. Secondly, there were 40 GBP Partner buildings for which no data on absolute energy savings were available (approx. 14% of the buildings).

The maximum absolute savings were achieved in Germany – more than 116 GWh/year, despite the fact that Germany is only second in terms of the number of Partner buildings. Sweden follows with total savings of 51 GWh/year, Spain being third with 19 GWh/year. When we relate the savings to the number of Partner buildings in these three countries, then the average savings per building are 1500 MWh/year in Germany, 480 MWh/year in Sweden and 1000 MWh/year in Spain. This reveals that both in Germany and Spain larger but fewer projects prevail, whereas in Sweden it concerns a great number of relatively small projects.

With regard to individual projects, the maximum absolute savings were achieved in a Test Centre for Transformers. The maximum primary energy demand that is legally required for such a building is 984.3 kWh/m^{2}a, whereas the Test Centre achieved the primary energy demand of only 23.3 kWh/m^{2}a, 97.5% less than required. In absolute terms, it gives a saving of 11.83 GWh/year.

In total, there were five buildings out of the 271 Partner buildings that reported on the percentage savings which had not achieved the 25% savings. The reasons for this are diverse. For example, there is one building which had reached only 19% savings. Nevertheless, the building was accepted as a GreenBuilding Partner because the energy consumption is 30% below the regulation in force. Similarly, another Partner building is only 21.5% below the legal requirements. However, there are photovoltaic and solar systems installed in the building, together with tri-generation plants, which can produce 160% of the primary energy demand of the building.

More than two thirds of the Partner buildings (179 out of 271) achieved more than 30% savings. The average achieved savings are 41.2%, the median is 36.5%. The maximum achieved savings on an individual basis were more than 97% (97.5%), through the use of district heating, efficient lighting and thermal insulation in the building.[4] There are five buildings in which primary energy savings of more than 80% have been achieved. In all cases, the measures included the building envelope and reconstruction of heating systems; in four cases efficient lighting was installed. Interestingly, there is one building from before 1900 which has reached high percentage savings. The former canteen and office building of an abattoir was reconstructed into a nursery house with offices. Despite the fact that the area of the building increased, the primary energy consumption decreased by 80%. The main measures included the building envelope, heating and hot water preparation (including floor heating, temperature regulation, installation of water saving sanitary equipment and an efficient gas condensing boiler). The important message is that the resulting primary energy consumption goes even beyond the current building requirements, thus showing that a low energy standard is viable even for historical buildings.

When it comes to building type, the average percentage savings range from 55% in commercial centres and leisure facilities (51%) to 28% at an airport ("Other" buildings). The relative savings in offices, the most important building type as regards the total savings and total number of buildings, averages 39%. It was ascertained that the absolute level of savings does not correlate with the year of construction. However, it is probably more surprising that neither does the relative level of savings. Therefore, one cannot say that the older the building, the higher the potential for savings. In historical buildings, the reason may be the restrictions as to cultural preservation of these buildings. Nevertheless, the correlation could not be found even for the buildings from the 20th century.

3.3. Specific energy demand in office buildings

One of the most important indicators of efficiency with respect to buildings is the primary energy demand per m^2 and year (kWh/m^2 y). At the same time, both building regulations for new buildings and the demand as such largely depend on the building type and consequently its use. Therefore, we specifically depict one building type for specific energy demand analysis. Office buildings are the most frequent building type in the GBP and thus offer the largest sample for analysis. In office buildings, energy consumption related to kWh/m^2 y is the most predictable and has been analysed in other studies [4]. Office buildings (together with retail stores) account for the highest share of energy consumption among non-residential buildings [5].

The sample consists of 167 office buildings, of which there are 100 existing buildings and 67 new buildings. The following analysis is divided according to this characteristic.

[4] It is a new building, thus the savings mean comparison with the respective legal requirements.

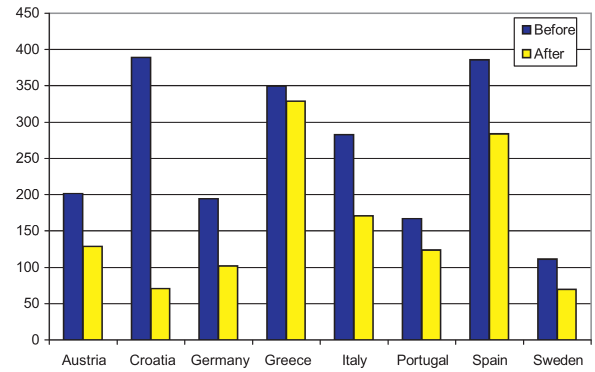

Fig. 5. Specific primary energy demand of existing office buildings before and after refurbishment (kWh/m^2 y).

3.3.1. Existing buildings

The average pre-refurbishment primary energy demand per m^2 of existing office buildings was 150 kWh/m^2 y. The lowest value was only 34 kWh/m^2 y. The maximum demand before refurbishment reached 558.4 kWh/m^2 y. The highest specific primary energy demand after refurbishment was 328.6 kWh/m^2 y, whereas the minimum value reached only 11.1 kWh/m^2 y, thus achieving the passive house standard.

On average, the energy efficiency measures brought a decrease in the specific consumption of 85 kWh/m^2 y. The highest absolute difference between the specific primary energy demand before and after refurbishment was 496.4 kWh/m^2 y (from 558 to 62 kWh/m^2 y), the lowest absolute difference reached 11.9 kWh/m^2 y (from 45.5 to 33.6, which means savings of 26%).

The building energy consumption in existing buildings seems on average the lowest in Sweden – approx. 100 kWh/m^2 y – where a lot of heating and cooling is supplied by district heating (Fig. 5). Conversely, the highest consumption of conventional buildings is observed in Spain, Croatia, Greece and Italy (over 250 kWh/m^2 y), thus also offering the highest potential for savings. This potential is clearly shown in the case of Croatia, where the average energy consumption after refurbishment decreased more than fivefold (from 390 kWh/m^2 y to 70 kWh/m^2 y). The existing office buildings in Sweden already tend to have a relatively lower specific energy demand (an average of 111 kWh/m^2 y). Nevertheless, the average difference between the values before and after refurbishment is 40 kWh/m^2 y, i.e., still 36% of the original primary energy demand.

3.3.2. New buildings

Fig. 6 depicts the increase in efficiency of newly constructed office buildings in the GBP. The reference values of the new buildings mean the building standards in force in the respective year to which the primary energy demand of the newly constructed buildings is compared, or it can be the level of consumption in reference with "conventional" newly constructed buildings in the country.

It is important to bear in mind that the values to which the new buildings are compared are not in every case representative of the current energy code requirements in those countries. Nevertheless, some patterns can be observed. The toughest requirements for GBP Partner buildings are in Denmark, Slovenia and Sweden. In Denmark the average primary energy consumption to which the newly constructed buildings relate is lower than 100 kWh/m^2 y (95.6); however, there was only one building in the sample. The average reference requirements in Slovenia are 122 kWh/m^2 y and 120 kWh/m^2 y in Sweden. The average specific primary energy consumption to which the new buildings are

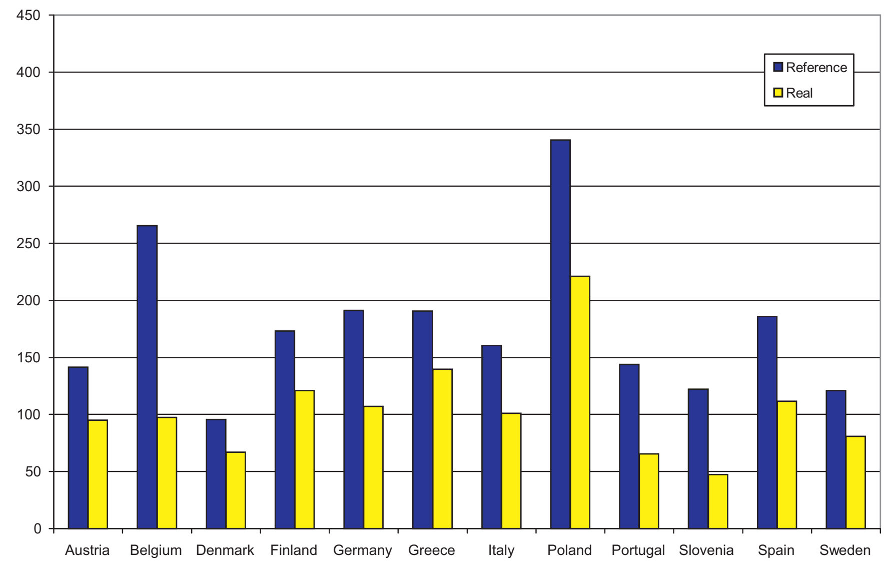

Fig. 6. Specific primary energy demand of newly constructed office buildings and related reference values (kWh/m^2 y).

compared is 170 kWh/m^2 y. The lowest reference value is a legal requirement for passive houses: 21.6 kWh/m^2 y.

The maximum absolute difference reached between the energy code requirement and the real energy demand of the building was 226 kWh/m^2 y (40 kWh/m^2 y instead of 266 kWh/m^2 y, which is the reference national standard).

On average, the new Partner buildings consume 72 kWh/m^2 y less than the respective national standards. The smallest achieved difference is only 10.7 kWh/m^2 y. However, the approximately 11 kWh/m^2 y means 50% lower consumption even compared to the tough passive house standards. The relative savings in new office buildings average 41.6%, thus slightly exceeding the overall average (41.2%).

3.4. Energy efficiency measures

The energy efficiency measures are what makes the energy efficiency improvement (or energy savings) possible. Out of the total of 286 Partner buildings, 226 of them (79%) have reported on the implemented measures.

Fig. 7 depicts the main measures in terms of their proportional representation in the projects. The graph follows the (sub)categories set up in Table 2 above. The percentage values mean the share of Partner buildings in which the given measure was implemented.

About 52% of energy in service sector buildings[5] in the European Union is consumed by space heating; heating systems (together with the building envelope) offer a significant potential for savings [6]. Therefore, the GBP Partners most often choose heating as their main target for efficiency measures. In Fig. 7, the reconstruction of the heating system (57% of buildings) entails reconstruction or dealing with the distribution systems within the building, use of district heating and/or conversion from one fuel type to another (not to biomass, but usually from oil to natural gas).

Additionally, depicted separately in Fig. 7, heat pumps have been used for heating in 14% of the Partner buildings. Where specified, these were universally geothermal heat pumps. In 7% of the Partner buildings, fossil fuel boilers have been replaced with biomass boilers. In one case, the boiler burns biogas.

Combined heat and power generation (CHP) was used in 5% of the buildings (some buildings are also connected to district heating from CHP: see the next paragraph). Altogether, heating systems have been upgraded or dealt with in 85% of the cases.

A very frequent measure is connection to district heating systems, as countries in which these systems are commonly utilised are highly represented among the GreenBuilding Partners (Germany and Sweden). Eight Partner buildings (from Germany and Austria) have connected the buildings to district heating from either renewable energy sources (biomass) or from cogeneration units. In one building, heat and power from a tri-generation plant is used and, together with solar and PV panels, the building produces 160% of the energy it consumes. Conversely, none of the Partners reported having disconnected the building from the district heating system.

More than 60% of the Partner buildings (61%) have focused on the ventilation/air conditioning and cooling systems. The measures mostly concern the heat recovery (from 75% up to more than 90%), replacement and proper dimensioning of pumps and fans (frequency transformers), resizing of the ducts or the overall system optimisation (zone regulation, optimisation of operation time, reduction of flow rates).

The building envelope represents further significant potential for savings. The Partners have included it in the main measures in 57% of the cases. Yet, the scope of the improvements of the envelope systems differs to a large extent. It ranges from total insulation of the building, including the whole building envelope (roof, facade, ground and windows), to only featuring some parts of the envelope (such as better glazing or low u-values of the facade). Specifically, the buildings are equipped with summer heat protection (11%), which basically means external shading devices to protect the building from excessive summer heat gains. The shading devices tend to be movable, electronically controlled and automated. There were several cases in which vegetation was used as a natural shading and air temperature reducing instrument.

[5] All the building types in the GBP come within the services sector, with the exception of the industrial buildings.

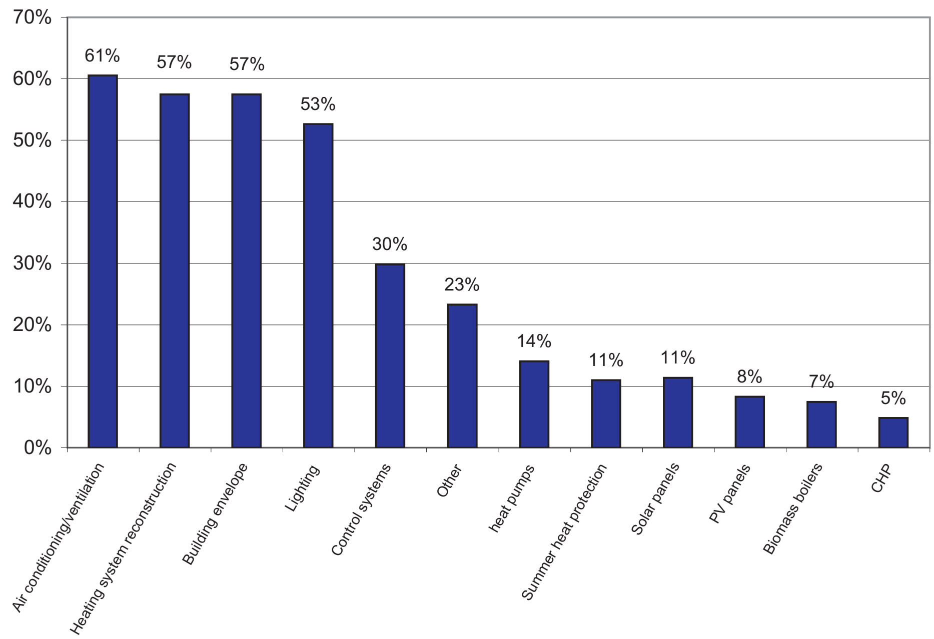

Fig. 7. Measures in buildings (%).

Lighting does not usually represent the highest portion of total energy consumption.[6] However, lighting also represents one of the most easily achievable energy efficiency improvements, usually with very short payback times.[7] That is why more than half of the GBP Partners (53%) have included lighting upgrading among the efficiency measures. The measures mostly entail the use of more efficient lighting (compact fluorescent lamps, efficient fluorescent tubes, electronic ballasts, LED lights). To add more savings, lighting is managed through motion/occupancy detectors, daylight sensors or through localised lighting.

The Partners frequently install building energy management and control systems (30% of the cases). The systems (the term often used is Building Energy Management System, BEMS) control and monitor all the buildings' (above-mentioned) equipment, such as HVAC or lighting.[8] The control systems also help in monitoring and evaluation of the energy consumption of the buildings, which provides a basis for further energy savings.

Other measures (23%) included water saving systems, activities to raise staff awareness and purchase of energy efficient appliances (mostly office equipment). The water saving system was often used in leisure centres and hotels, which include spas and swimming pools, but also in hospitals, where the use of sanitary hot water is high. The systems include use of rainwater, hot water recovery systems and low-flow taps.

One fifth of the buildings have installed a photovoltaic system or solar panels (8% and 11%, respectively). The installed powers of the PV systems differ greatly. They range from small systems of 4–5 kWp to tens of kWp. There is one photovoltaic power plant with 1 MW installed capacity. The total installed capacity in GBP buildings amounts to approximately 1400 kWp. The area of the solar panels ranges from 5 m^2 to 300 m^2.

The effectiveness of solar systems largely depends on climatic conditions. It is therefore not that surprising that (even though there are exceptions) the solar and PV systems have mostly been used in southern countries rather than northern ones. Most frequently (% of the Partner buildings in the country) the PV or solar systems were used in Slovenia, Portugal and Italy (67%, 62% and 44%, respectively). There is also Hungary (not a typical representative of a southern country) with 50%. However, the high percentage in this case pertains to the total number of buildings (2). The solar and PV systems are far less present in Austria, Germany and Sweden (17%, 11% and 2%, respectively).

On the other hand, among the GreenBuilding Partners there is no evidence that the implementation of building envelope measures is associated with specific climatic conditions or geographical distribution (Fig. 8).

The Partners implement 3.4 measures per building on average. The relation between the number of measures and relative savings (%) is shown in Fig. 9. The numbers on top of the columns represent the number of buildings in which the respective number of measures was implemented.[9] In respect to the average number of measures, Figure 9 shows that in most buildings three to four measures have been implemented.

There is a statistically significant relationship between the variable number of saving measures and percentage savings (on a 99% confidence interval). However, the relationship is very weak and the fitted models only explain 10% of the variability. It means that, based on the sample, no real (significant) correlation between the number of measures and the percentage savings has been found (only a weak one). Nevertheless, the highest average savings are achieved when four to five measures are implemented (47.7% and 48%, respectively).

[6] For instance, as to [7] lighting represents approx. 11% of energy consumption in the tertiary sector (and 21% of tertiary electricity consumption), five times less than, e.g., space heating.

[7] Similarly to GBP there is also the GreenLight Programme, which is a voluntary programme focused specifically on lighting.

[8] The building management system can be further used to control security or fire systems.

[9] The "number of measures" means how many measures, structured as the main categories in Table 2, were implemented in the respective building.

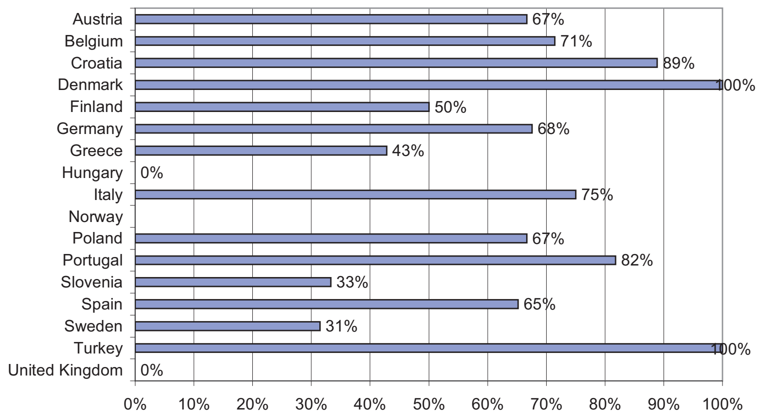

Fig. 8. Measures in building envelope per country (%).

Table 3
Economic aspects of the GreenBuilding Partner buildings.

Cost of investment (EUR)	Financial savings (EUR/year)	Payback time (years)	Average savings (MWh/year)
683,744	84,837	9.6	1334

The most frequent combination of measures is HVAC (heating and air-conditioning and ventilation), which was implemented in 50.7% of the buildings that reported on measures. The second most frequent combination is heating and building envelope (50.2%). The three most common measures that are implemented together in the GBP buildings are heating, building envelope and lighting (31.7% of cases), followed by heating, air-conditioning and ventilation and building envelope (29.1% of cases). The combinations therefore closely follow the distribution of measures presented in Fig. 7.

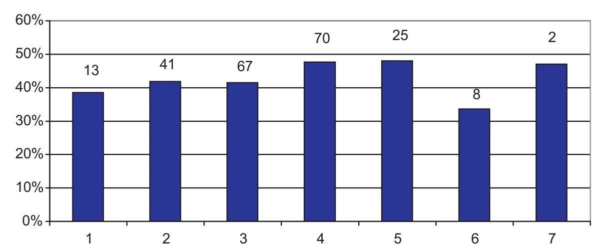

Fig. 9. Average savings (%) per number of implemented measures in the Partner buildings.

3.5. Economic aspects of selected projects

The economic effectiveness of the projects is one of the prerequisites to become a GreenBuilding Partner and only a few Partners have reported on this. The economic aspects of the GreenBuilding Programme buildings could therefore be evaluated only to a limited extent. Also, there is no common format to report on the economic features. Therefore, the Partners reported different economic indicators, such as pay back time, Net Present Value (NPV), Internal Rate of Return (IRR), cost of the investment or the annual cost savings.

Only a small fraction of Partners (22, i.e., less than 8% of the Partner buildings) reported on the financial features of the energy efficiency investment. The main conclusions from their reporting are shown in Table 3.

There were 30 Partners who reported the costs of the investment.[10] In the case of new buildings, only additional costs for the energy efficient measures were included. On average, the cost of 1 kWh/year saved was EUR 0.21, or the opposite way, on average 131 MWh/year were saved for EUR 1 of (additional) investment. This result is, however, skewed by one Partner building in which the savings were achieved at zero cost. If this one case were disregarded, then EUR 1 of investment corresponds to 32 kWh/year. When looking at the payback times of the investments, the numbers vary greatly (Fig. 10).

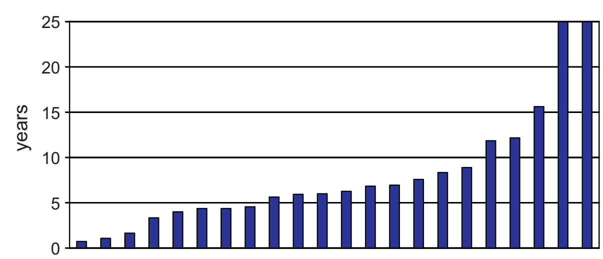

Fig. 10. Simple payback of the measures. *Note*: The payback was calculated for 22 Partners who reported both cost savings and the investment costs. The last two columns represent paybacks of 40 years.

The average simple payback time is 9.6 years. There are several extreme values in the sample (e.g., a payback period of several decades[11]). Therefore, the median (6.3 years) probably better describes the mean value. There are seven buildings in which the payback time varies around one to four years. Some Partners set a low payback time (of less than three to four years) as a requirement for the energy efficiency measures and adapted the measures

[10] Plus there was one Partner who reported the costs but the overall savings were not available.

[11] There was one building in which the simple payback period exceeded 100 years. However, there may have been a mistake in the recordings. This extreme value was disregarded for the calculation of the average.

accordingly (implementing less costly measures with a short payback time, such as, e.g., lighting).

Five Partners have reported the values of Internal Rate of Return (IRR) or Net Present Value (NPV) of the projects. The IRR ranged from 9% to 20% and the NPV from EUR 6800 to 330,000. For other investments, it may be assumed that the levels of NPV or IRR correspond to the GreenBuilding Partnership criteria.

4. Conclusions

Within the four-year operation of the GreenBuilding Programme, a total of 167 Partners have joined with 286 Partner buildings. The total savings achieved by the Partners are 304 GWh/year. In 2020, the savings will have accumulated to almost 3.3 TWh. On an individual basis, the maximum savings per project were 11.8 GWh/year (4% of the overall savings).

Office buildings are the most represented building type among the Partner buildings and therefore also represent almost half of the total savings (141 GWh/year). Among countries, the highest savings so far have been achieved in Germany and Sweden, together accounting for more than half of the savings (166 GWh/year). The average percentage savings amount to 41%, which is well above the GreenBuilding Programme requirements (25%). The highest average relative savings have been achieved in commercial and leisure centres (55%).

There is only a weak correlation between the number of measures and percentage savings. Furthermore, the percentage savings (statistically) depend neither on the building type nor on the year of construction of the buildings. From the analysed data it is not possible to conclude that the older the building, the higher the potential for savings. Not even for the buildings constructed in the 20th century (which most probably cannot be classified as historical buildings) has such a correlation been found. However, the case examples among the GreenBuilding Partners show that primary energy consumption even in historical buildings can go far beyond the respective (current) building requirements and such reconstructions are economically efficient.

The office buildings have been assessed as to their specific energy demand (in kWh/m^2 y). In the refurbished office buildings the average decrease in the specific primary energy demand was 85 kWh/m^2 y. The analysis of GBP office buildings shows that large potential for savings exists where the original consumption is high; however, this potential does not seem to be fully utilised in all cases. On the other hand, even when the original energy consumption is relatively low, the potential for savings remains significant (tens of %).

On average, the new office buildings consume 71 kWh/m^2 y less than respective building codes in force. The studied cases show that the Partner buildings can attain energy consumption far below the reference standards (while respecting the economic efficiency of the projects) and even below the passive house standards.

In most of the GBP buildings, to achieve the above savings more than one energy efficiency measure has been implemented. Most often, it is a combination of three to four measures, but the highest average percentage savings were achieved through a combination of four to five measures. Most frequently, these entailed heating (85% of the buildings), air-conditioning and ventilation (60%), building envelope (58%) and lighting (53%). The reasons for implementing a number of measures at once are economic effectiveness as well as design needs. If not done at once, it may leave some of the measures unimplemented as there may not remain sufficient potential for savings [8].

The use of sun (photovoltaic and solar panel installations) is much more prevalent among GBP Partners from southern European countries. However, the focus on building envelope (and heating) is common to most projects without relation to geographical location.

Economic effectiveness is a prerequisite for joining the GreenBuilding Programme, all of the projects are assumed to be economically viable. This is one of the reasons why the Partners have rarely reported on the economic features of the projects.

The GreenBuilding Programme has been successful over its four-year operation. The number of Partners is growing steadily. The aim now is to promote these good practice examples to a wider public.

References

[1] European Commission (EC). Action Plan for Energy Efficiency: Realising the Potential. COM(2006)545 final (2006). http://ec.europa.eu/energy/action_plan_energy_efficiency/doc/com_2006_0545_en.pdf.
[2] N. Pillen, P. Bertoldi, S. Grether, GreenBuilding – Europe wide renovations of non-residential buildings, in: S. Attali, K. Tillerson (Eds.), Proceedings of the ECEEE 2007 Summer Study: Saving Energy – Just Do It! ECEEE, Stockholm, 2007, pp. 1019–1025.
[3] M. Valentova, P. Bertoldi, Analysis of the building owners' motivations for investing in energy efficiency: results from the GreenBuilding Programme, in: Proceedings of the IEECB'08 Conference, Frankfurt, 2008.
[4] S. Plesser, T. Wilken, N. Diech, EVA – Evaluation of Energy Concepts for Office Buildings, in: Proceedings of the IEECB'06. Improving Energy Efficiency in Commercial Buildings (2006). http://re.jrc.ec.europa.eu/ energy-efficiency/pdf/publications/IEECB06proceedings%20Vol1.pdf.
[5] L. Pérez-Lombard, J. Ortiz, C. Pout, A review of buildings' energy consumption, Energy and Buildings 40 (3) (2008) 394–398.
[6] The GreenBuilding Programme (GBP), The technical modules: Heating. http://re.jrc.ec.europa.eu/energyefficiency/greenbuilding/pdf%20greenbuilding/GB_WP2_HEATINGModule_V2_BE.pdf (2006).
[7] P. Bertoldi, B. Atanasiu, Electricity Consumption and Efficiency Trends in the European Union. Luxembourg: Publications Office of the European Union (2009) http://re.jrc.ec.europa.eu/energyefficiency/pdf/EnEff_Report_2009.pdf.
[8] P. Bertoldi, M. Valentova, The European GreenBuilding Programme 2006–2009 Evaluation, Publications Office of the European Union, Luxembourg, 2010.

Annex 6

‘Ex-Post Evaluation of Energy Efficiency Programmes: Case Study of Czech Green Investment Scheme’ *(Valentová, Karásek, and Knápek 2018*)

Received: 4 December 2017 | Revised: 9 May 2018 | Accepted: 10 July 2018
DOI: 10.1002/wene.323

WILEY WIREs ENERGY AND ENVIRONMENT

OVERVIEW

Ex post evaluation of energy efficiency programs: Case study of Czech Green Investment Scheme

Michaela Valentová | Jiří Karásek | Jaroslav Knápek

Faculty of Electrical Engineering, Czech Technical University in Prague, Prague, Czech Republic

Correspondence
Michaela Valentová, Faculty of Electrical Engineering, Czech Technical University in Prague, Technicka 2, Prague 6, Czech Republic.
Email: michaela.valentova@fel.cvut.cz

Funding information
Technology Agency of the Czech Republic, Grant/Award Number: TJ01000066

A significant amount of financing has been available for improvements in energy efficiency in buildings in recent years. However, careful evaluation of the real impacts of the programs is still inadequate. The paper provides an insight into the relationship between the expected outcomes and the actual results of an energy efficiency program. It does so on a case example of one of the most significant energy efficiency and renewable energy sources programs in Central Europe, the Green Savings Programme. In total, 206 measures were inspected in 124 projects of the program. The analysis of the inspections showed that there is a significant difference between the expected, verified CO_2 emission reduction and ex post, real attained reduction (25% on average). The reasons are partly methodical, but most can be attributed to the behavioral factors of occupants in the respective buildings. The results therefore clearly show the need to tackle the relationship between the calculated (expected) energy savings (and related CO_2 emission reduction) and the real savings which are highly influenced by building users. Ex post evaluations should be done, among other things, to provide a more accurate picture regarding the member states' energy efficiency improvement obligations. Furthermore, such evaluation also provides an essential input for further optimisation of the future energy efficiency support programs.

This article is categorized under:
Energy Efficiency > Economics and Policy

KEYWORDS
energy efficiency, Green Investment Scheme, policy evaluation, prebound effect

1 | INTRODUCTION

The buildings consume about 40% of energy in developed countries and about 75% of buildings in the European Union (EU) Member States are considered as insufficient regarding energy efficiency (European Commission, 2016). Therefore, there is still a significant potential for improvement of the buildings stock and a decrease of energy consumption. To this end, many supporting schemes regarding EU operational programs or programs at the national level have been set up. However, the pace of improvement is still not high enough, and neither is the level of monitoring and evaluation.

There has been a vast amount of literature on the expected outcomes of various energy efficiency, renewable energy sources (RES), and greenhouse gas (GHG) emission schemes and programs (cf. Carley & Browne, 2013; Clinch & Healy, 2001; Karásek & Pavlica, 2016; Sayeg & Bray, 2012). However, the level of detail and accuracy of the monitoring system of the programs varies greatly (Le Den et al., 2016). Furthermore, the number of ex post evaluations of the real outcomes of such programs is still inadequate (Le Den et al., 2016; Webber, Gouldson, & Kerr, 2015), especially in small-scale projects.[1] Monitoring of achieved energy savings is not usually implemented and comparative studies on ex post evaluation are still missing. The current paper, therefore, contributes in this field by covering ex post evaluation of considerable variability of measures, including the behavioral aspect of energy consumption.

The paper evaluates the outcomes of the Green Savings Programme, result of the Green Investment Scheme (GIS) in the Czech Republic. Based on the evaluation of ex post inspections which took place toward the end of the program, it analyzes to what extent the expected energy savings from the subsidized projects turned into actual energy and emission reductions. Furthermore, based on the inspections combined with qualitative interviews with the applicants, it analyzes and discusses the reasons behind the differences in expected (ex ante) and real (ex post) results. The paper, therefore, contributes to the current academic debate by providing a thorough insight into the real outcomes of the energy efficiency subsidy program. The results of the inspections offer a valuable input in the future design of programs as well as evaluations of other, similar policy measures.

The subsequent sections are structured as follows: The second section presents the Green Savings Programme including the main outcomes of the program, types of applicants, and measures. It is then followed by a methodological section, which describes the organization of the inspections, the methods for data acquisition and indicates the logic behind the calculation of CO_2 emission reduction. In the fourth section, the quantitative results of the inspections are presented. The next section then provides an insight into the reasons behind possible differences between ex ante and ex post calculations. A particular focus is placed on the qualitative aspects of the subsidized measures such as the social impact on households. The last section concludes and conveys policy implications of the research.

2 | GREEN SAVINGS PROGRAM – OVERVIEW

The GIS is an influential tool to reduce GHG emissions. The states in the GIS are obliged to invest the funds gained through the sale of Assigned Amount Units (AAUs) in GHG emission saving and environmental protection programs. Under the Kyoto Protocol for the period of 2008–2012, the Czech Republic achieved an assumed emissions surplus of about 150 million tons of $CO_{2\text{-eq}}$. (AAUs). About 100 million AAUs could be traded under the international emission trading mechanism (Karásek, 2011).

The GIS in the Czech Republic has taken the form of the Green Savings Programme (further also referred to as the Programme) which ran from 2009 to 2012 and supported energy efficiency and RES measures in residential buildings. These measures led to an immediate reduction of CO_2 emissions and will kick-start a long-term trend of sustainable construction. The State Environmental Fund of the Czech Republic (SEF) has been entrusted with the management of the Programme.

Calculation of CO_2 emission reduction was carried out under the Programme. The CO_2 emissions reduction has been achieved by implementing the Green Savings Programme based upon the applications registered, approved, and paid until December 31, 2013 across assisted areas. The calculations of CO_2 emission reduction were provided by SEF, according to a validated calculation method devised for the calculation of CO_2 emission reduction under the Green Savings Programme (Honzík et al., 2014).

According to the Annual Report of the Green Savings Programme in 2013 (SEF, 2014), the total number of applications registered under the program was 74,117. In total, 80,696 projects were registered by the end of 2013, and the overall disbursed subsidy of applications registered by December 31, 2013 exceeded CZK 20.29 billion.

By December 31, 2014, most of the projects under the Green Savings Programme 2009–2012 already had been provided with the subsidy. The only projects discussed in 2014 (remaining a few hundred projects) were the ones that showed some technical or administrative defects. According to the information provided by the SEF, all these projects were completed in 2014. Within the expected lifespan of 15 years, the total reduction of CO_2 emissions was calculated at 11,765,150 tons.

Figure 1 captures the structure shared by individual subsidy areas in the number of applications, investment costs, allocated subsidy, and CO_2 emissions reduction. By comparison, this figure identifies measurable costs of reduction regarding subsidies, as well as total investment costs.

Figure 2 shows that the most effective emission reduction was achieved from biomass boilers and heat pumps with the highest share between CO_2 emission reduction and subsidy, that is, the highest greening ratio. The greening ratio means that the higher ratio achieved, the better efficiency of financial sources reached.[2] The least effective area from this point of view was passive energy building standards as the reference consumption is already low.

3 | METHODS

3.1 | Research framework

The methodology chosen to evaluate the results of the Green Savings Programme has two parts. The first part consists of a comparison of metered (invoiced) data with standardized, ex ante data registered in project documentation of the applicants in

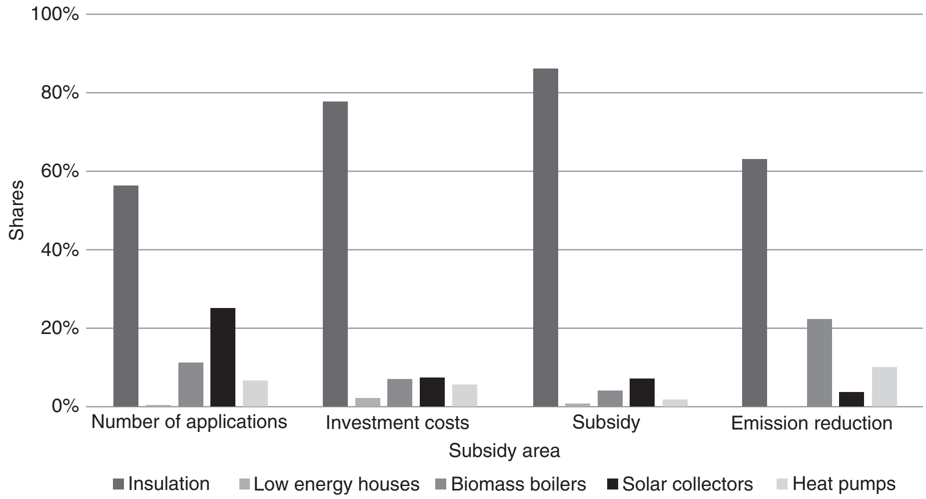

FIGURE 1 Comparison of subsidy areas via shares on number of applications, investment costs, subsidy, and emission reduction (Karásek & Pavlica, 2016)

the Green Savings Programme. The second part then relies on the qualitative evaluation of the reasons behind the difference between the expected and real outcomes of the projects. The qualitative part is based on semi-structured interviews with the applicants. On-site inspections were carried out to obtain the data.

3.2 | Preparation of the inspections and sampling

In 2012, SEF, the administration body of the Green Savings Programme, launched a verification procedure of the outcomes of the subsidized projects. Such procedure was a condition set by the buying parties of the AAUs. During this process, a total of 206 inspections of energy efficiency measures was carried out to verify the achieved energy and CO_2 emission reduction. The present paper builds on these inspections to evaluate the real outcomes of the projects supported by the program.

Often, the applicants bundled energy efficiency measures together (this was also supported by the program in the form of a bonus). Therefore, in 78 cases, two to three measures were inspected in one site—that is, a combination of two to three energy efficiency and RES measures was carried out by a single applicant. In total, 124 projects (applicants) were therefore inspected.

The sample for inspections was selected from a list of applications by the administrative body in cooperation with the company carrying out the inspections. Only applications in which the measures were implemented at least 18 months ago were selected. The list of applications contained all relevant data for emission reduction calculations and the calculated CO_2 emission reduction. The list was further complemented with specific documentation of selected applications, such as energy savings calculation, project documentation, and application for the Programme, to make the inspections more relevant.

The sample reflected both the regional diversity of the projects and the diversity in types of measures. The aim was to cover all 14 regions of the Czech Republic and also to cover sufficiently all of the supported areas (insulation, low-energy

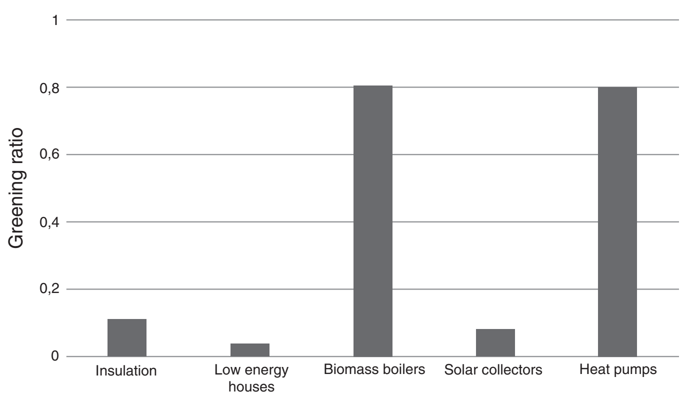

FIGURE 2 Greening ratio of the subsidized measures (Karásek & Pavlica, 2016)

TABLE 1 General CO_2 emission factors according to Decree no. 425/2004 Coll

General CO_2 emission factors (t CO_2/MWh calorific value)				
Coal	**Light fuel oils**	**Natural gas**	**Electricity**[a]	**Biomass**
0.36	0.26	0.2	1.17	0

[a] t CO_2/MWh electricity

houses, biomass boilers, heat pumps, and solar-thermal systems). Also, the inspectors gave particular preference to combinations of the measures, that is, projects in which two to three types of measures were combined. The reason for this was mainly to have better knowledge of these types of projects, which were to be preferred in the future rounds of the program.

3.3 | Inspections

It was decided to carry out direct interviews with the applicants. Two-member teams visited each site-project. Compared with, for example, phone or e-mail interviews, such approach allowed to tailor the questions and to lead the interviews depending on the actual situation at the site and on the quality of documents provided by the applicants. Such method also allowed to understand the approach of the applicant better and increased the trustworthiness of the results. In the end, it has also decreased the administrative burden of the inspections.

On-site, the process of inspection went as follows:

- Controlling of the project documents;
- Determination of the real energy consumption before and after implementation of the measures, based on energy invoices (and other relevant available data);
- Compliance check of the implemented measures to the project documentation, photo documentation;
- Protocol on the inspection.

3.4 | Evaluation

After each round of inspections (in total three), a report on the inspections was elaborated containing quantitative and qualitative analyses.

Based on available data (energy invoices), the inspectors further examined the real ex ante and ex post energy consumption and compared it with the calculated energy and CO_2 emission reduction from the project documentation.

The CO_2 emission reduction was calculated as the difference between the CO_2 emissions before and after the implementation of the energy efficiency and RES measures within the Green Savings Programme. The calculation used the general CO_2 emission factors as to Decree No. 425/2004 Coll. (Ministry of Industry and Trade of the Czech Republic, 2004). The emission factors are summed up in Table 1.

Hereafter, an example of the calculation of CO_2 emission reduction for individual subsidized measures in the Green Savings Programme is provided. More details on the calculation methods can be found in Honzík et al. (2014).

The data were collected from the information included in the applications and stemming from respective energy audits. Equation (1) shows the calculation of CO_2 emission reduction for insulation measures.

$$Savings\left[\frac{tCO_2}{year}\right] = \left(c_{bf} * s_{bf} - c_{af} * s_{af}\right) * 3.6 * K_e / 1000 \quad (1)$$

where c_{bf} is specific annual heat demand in the building before implementation of the measures (kWh/m^2.a), s_{bf} is total floor area of the building before implementation of the measures (m^2), c_{af} is specific annual heat demand in the building after implementation of the measures (kWh/m^2.a), s_{af} is total floor area of the building after implementation of the measures (m^2), K_e is corrected CO_2 emission factor according to the type of initial heat source (tCO_2/GJ_{corr}).

Similarly, the ex post evaluation was based on the structure of energy carriers consumed in the building and on invoices scanned during the on-site inspections. During the evaluation process, the respective consumption was compared with the ex ante consumption. According to the energy carrier related CO_2 emission factor was selected (see Table 1) and the CO_2 emission reduction were calculated.[3] There are some specifics in the program influencing deviations between energy savings and CO_2 emission reduction for ex ante and ex post evaluation.

The difference between the deviations of the energy savings and CO_2 emission reduction depends on the difference between the emission factors applied. The emission factors used for ex ante evaluation were different from the emission factors used for ex post evaluation because ex ante evaluation did not fully cover efficiency of the heating system and this was corrected via emission factors. The ex ante emission factor includes average efficiency of the heat source and average mix of

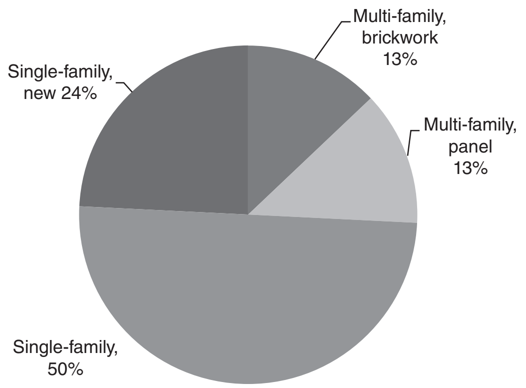

FIGURE 3 Structure of the inspected objects according to the type of buildings

energy carriers, for example, for district heating mix of coal and biomass. The national Decree no. 425/2004 Coll. provides the emission factors for ex post evaluation according to the main energy carriers. The results for single measures are influenced by the emission factor used. However, statistically the impact is very low. The quantitative analysis of the measures covered comparison of the CO_2 emission reduction.

In addition, the inspectors carried out qualitative, semi-structured interviews with the applicants to examine further relevant factors that may have influenced the final energy consumption in the inspected objects (such as the use of the building, thermal comfort, occupancy of the building, additional heat sources, and other). A discussion with the building owners about the process, initial expectations, duration of construction works, and overall satisfaction was an essential part of the interview. The discussion took about 20 min and usually brought explanations to the differences in ex ante and ex post evaluation.

4 | RESULTS

In total, 206 measures were inspected in 124 objects (buildings) toward the end of the Programme. In 10 inspections (5 objects), the meeting with the applicant did not happen due to unexpected circumstances on the side of the applicant, therefore, in such cases, the verification of the results and implementation of the measures could not be made. However, all 206 inspections (inspected measures and objects) are covered in the overall statistics on types of measures and types of buildings, as the measures were carried out.

Roughly three-quarters of the inspected buildings (out of 124 inspected objects) were single-family houses; the rest were multifamily (apartment) buildings. Of the single-family houses, one third were newly built houses—all in a low-energy standard, as this was the condition of the Programme. Of the apartment buildings, half were panel houses (Figure 3).

Over a third of the inspected measures (out of the total of 204 inspected measures) entailed partial or complete thermal insulation of the buildings (Figure 4). While complete thermal insulation, including the whole building envelope, was carried out majorly by multifamily houses, partial thermal insulation was preferred by applicants in single-family houses (75% of partial insulations in the sample were single-family houses). In total, 15 single-family houses in the low-energy standard were inspected (7% of all the inspected measures). Another 17% of the measures covered the installation of new low-emission biomass boilers (either as a replacement of an old, inefficient boiler or as a new installation) and in 13% of the cases, heat pumps were installed. Twenty nine percent of the measures entailed installation of solar–thermal systems (more than a third only for hot water preparation, 64% both for hot water preparation and additional heating).

The inspections do not entirely copy the structure of measures in the whole Programme. For instance, in the inspections, low-energy houses were higher represented than in the whole population (all projects supported by the Programme). Conversely, the share of insulation was lower within the inspections, than in the whole Programme (cf. Figure 1). The reason for this lies in the approach to the selection of the sample for inspections.

Importantly, in 39 cases the verification of the real attained energy savings could not be performed. The main reasons (apart from the above-mentioned five cases, during which the inspection did not happen) were mainly twofold: the unavailability of invoices (and irrelevant data provided by the applicants) and low level of detail of the invoices.

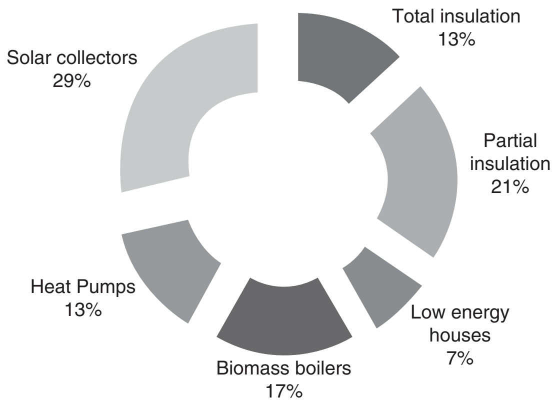

FIGURE 4 Structure of the inspected measures

Firstly, in about half of the cases, the reason why verification could not be made was that the applicants did not manage to provide the energy invoices from before and from after implementation of the measures. Furthermore, sometimes the data provided were irrelevant for the calculation of the energy consumption: for example, the applicant provided the invoice for the purchase of natural gas, but no data for actual consumption.

Relatedly, in multifamily buildings, the applicants provided invoices only for selected apartments, not the whole house or all apartments. It was not possible to extrapolate from such data to the whole consumption of the building. Therefore, the calculation could not be made, either.

Secondly, in half of the cases, the invoices for energy (specifically, electricity) consumption were available. However, it was impossible to extract the specific data on consumption of heat pumps (or solar-thermal systems, and other) from the rest of the home appliances. In some inspections, an expert estimate of the consumption of the high and low tariffs was made. However, this was not possible in all the cases, and moreover, the level of precision of such calculation may be rather low. In addition, the ex post calculation was not carried out for the newly built (low-energy) houses (15 cases). The invoices were not available as the houses were either not put to use at the time of the inspection yet, or have been in use only for a part of the year. Therefore, only partial invoices would be available and did not allow for the comparison of energy consumption. Furthermore, even if the data was available, the real energy consumption in the building can only be compared to the value of a reference building, due to the nonexistence of "before measures" data.

The comparison between the ex ante verified and ex post evaluation could, therefore, be made in 74 objects in total. In 57 of those cases, the ex post CO_2 emission reduction was lower than the ex ante values, whereas in 17 cases, the ex post CO_2 emission reduction was higher than the ex ante evaluation. Figure 5 shows the histogram of the calculated differences between ex ante (expected) and ex post (real) data. On average, the difference between the two values was 25%, meaning that on

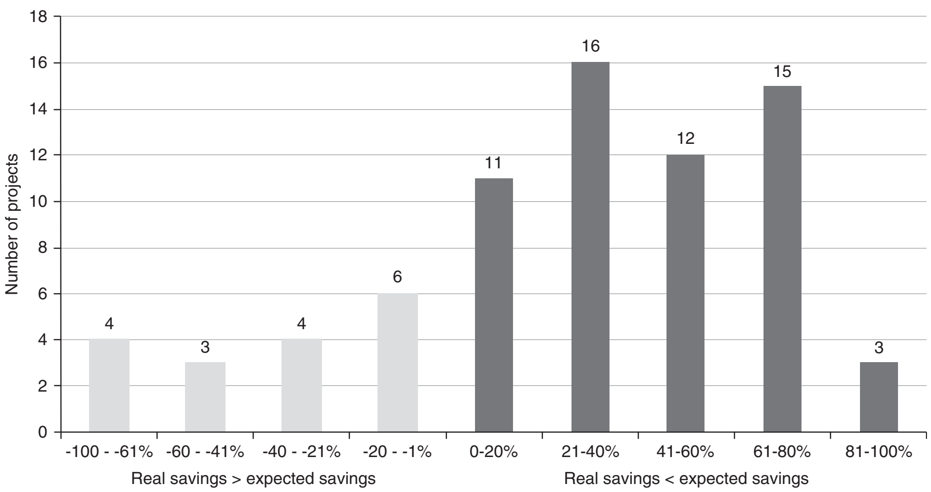

FIGURE 5 Percentage difference between the expected and real CO_2 emission reduction of the inspected projects

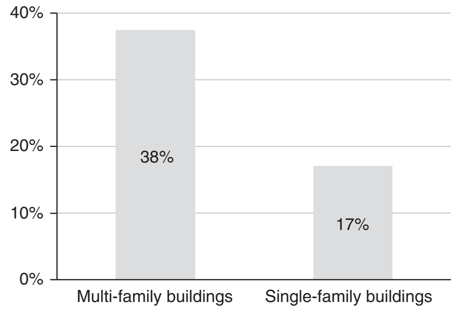

FIGURE 6 Share of inspected objects with higher real than expected CO_2 emission reduction

average, the ex post data were 25% lower than the ex ante outcomes as calculated in the project documentation of the applications. The median was 32%.

The CO_2 emission reduction at multifamily buildings seems more stable than in single-family buildings. In the sample, there is a noticeably higher share of multifamily buildings, for which the ex post CO_2 emission reduction was higher than the ex ante reduction—38% for multifamily buildings compared to 17% for single-family buildings (Figure 6). The reasons for this are mainly the more compact proportions and stable consumption in multifamily buildings, the higher discrepancy between the total floor area and actual heated floor area in single-family buildings compared to multifamily buildings. Furthermore, the indoor temperatures in individual apartments in the multifamily buildings will in total converge toward an average temperature, approaching the normalized values. All these factors lead to the fact that the normalized calculations used in ex ante evaluations may better reflect the real use of the multifamily buildings.

The average deviation between the real and expected CO_2 emission reduction of the combination of measures is twice higher than the deviation of the single measures (15.5% for single measures compared to 30.3% for the projects with combinations of measures). There are several reasons for that. Firstly, the combined measures have higher average savings (e.g., combination of building envelope and heat source). Secondly, there is much higher impact of the user in combinations of measures, especially in operation of the heat source, set up of the indoor temperature and number of rooms heated. Thirdly, the calculation method of CO_2 emission reduction does not fully cover reduction of the savings for combined applications. For instance, installation of the solar-thermal collector usually influences the heating system. However, calculation of this negative synergy for thousands of applications is complicated.

The highest CO_2 emission reduction has been attained through the installation of biomass boilers (with feeders or accumulator tanks). Heat pumps were found to be suitable in places where natural gas or biomass is unavailable. Solar-thermal systems have a lower impact in single-family houses as they mainly influence hot water preparation. They seemed more effective at multifamily buildings.

On the other hand, biomass boilers replacing the coal boilers are not economically effective, that is, do not have return on investment, even if the efficiency of the new heat source is higher. The reason is that the cost for coal is significantly lower than the cost for the biomass pellets. It seems that the owners decide on the replacement mainly because of increasing comfort and positive environmental impact.

5 | DISCUSSION

5.1 | Factors influencing the ex post evaluation

The inspections revealed that the reasons, why differences in ex ante and ex post results occurred, can be categorized into two main areas: methodical factors and behavioral factors. The two groups are discussed in detail in the following sections.

5.1.1 | Methodical factors

Firstly, the method of calculation of energy performance of buildings for the ex ante energy and CO_2 emission reduction in the Czech Republic is given by the Decree no. 78/2013 Coll. on Energy Performance of Buildings (Ministry of Industry and Trade of the Czech Republic, 2013). It is based on the standardized use of buildings, disregarding (due to methodical constraints) the differences in the usage by individual end-users. The inspections, therefore, revealed that the standardized values of energy consumption tended to differ from the real consumption (before the implementation of the measures), resulting in discrepancies between the ex ante and ex post evaluations. Relatedly, temperature differences in different years are not taken into account in the ex post calculations, which also may have caused divergences between the ex ante and ex post calculations.

In case of larger projects, such as multifamily dwellings, such differences could be mitigated if real consumption was taken as the background for savings calculations, for instance, an average consumption in the last 3 years, adapted to the long-term climatic average. In case of the Czech Republic, such procedure would be in line with the Decree on energy audits (Ministry of Industry and Trade of the Czech Republic, 2004).

Furthermore, in some cases, the interviews with the applicants during inspections revealed that wood firing in a fireplace was used to increase thermal comfort in the buildings before implementation of the energy efficiency measures. However, such consumption could not be included in the ex ante calculation for the project application. This in turn may have skewed the results of the ex post inspections.

Similarly, the inspections revealed that in some cases, the heat source was incorrectly categorized in the application, which meant that a different (higher) emission factor was used in the project calculation, artificially increasing the expected CO_2 emission reduction of the project. In one case, the applicant built an extension to the house, while insulating the house, and almost doubled the floor area of the building. Real consumption of the house therefore almost doubled after implementation of the measures.

5.1.2 | Behavioral factors

The inspections showed that large part of the differences in ex ante and ex post values in the projects could be attributed to behavioral aspects of the home-owners.

Firstly, the applicants asserted they changed partly the way they use their homes after implementation of the measures with different impacts on energy consumption. For instance, thanks to insulation, one applicant claimed they started heating up the cellar of the house, which was not previously heated. Another applicant said they only rarely used the newly insulated parts of the house. Both factors are resulting in lower energy and CO_2 emission reduction than expected in the project documentation.

Conversely, one applicant stated she just ended her parental leave at the same time that the energy efficiency measures were implemented, which resulted in higher real energy savings than expected in project documentation. Before implementation of the measures, the house was heated the whole day, whereas, after implementation of the measures (coinciding with the end of parental leave), the house is now heated only in the morning and in the late afternoon and evening.

In one case, the occupancy of the building changed in the course of the implementation of the measures, increasing from one to four, therefore increasing the real ex post energy consumption and lowering the resulting energy and CO_2 emission reduction compared to the calculated reduction in project documentation. Conversely, in one multi-apartments building, the actual occupancy was lower than in the projections. That also makes the ex ante and ex post data incomparable.

In several cases, the applicants reported they used wood firing in a fireplace to help heat up their space. In some cases, the heating in the fireplace was reduced after implementation of the energy efficiency measures (specifically, insulation, change of the main heat source). However, such heat consumption is hard to be precisely evaluated and incorporated in the calculations. Therefore, it skews the real energy and CO_2 emission reduction.

From the data, it cannot be directly said what the relationship between the factors above and the resulting difference in ex ante and ex post savings is. Often, it is a combination of the factors. In other words, the size of the difference, including the extreme values (as presented in Figure 4) seems to be rather case specific. More inspections would be needed to allow for deeper analysis of the various factors and specificities pertaining to different measures.

5.2 | Qualitative aspects of the implemented measures

Apart from a quantitative evaluation of energy and CO_2 emission reduction, the inspections also allowed for qualitative assessment of the measures and their implementation, as well as subsidy administration.

One of the primary goals of the inspections was to assess the overall quality of the implementation of the measures. The inspections found that there were no visible deficiencies in the realization at none of the inspected projects. One of the reasons for this might be that the subsidized measures could only be carried out by suppliers certified in the Green Savings Programme. Relatedly, with a few exceptions, the applicants expressed overall satisfaction with the implementation of the measures—both with the certified suppliers and with the fact they could realize the energy efficiency and RES measures.

The applicants that have decided to build their houses in low-energy standards almost unanimously reported that they were happy with the construction companies and the realization of the house. In 2 cases out of 14, the applicants stated they were unhappy with the construction company (and construction supervisor), and, either did most of the work themselves or hired a foreign construction company. It was caused mainly by the higher complexity of the projects. It means that the more complex the project is, the lower the number of construction companies that can finalize the project in a sufficient quality. It brings new changes to the nearly zero energy buildings and deep energy renovations. There are already construction companies focused on high standard housing in place. However, their share of the market is still low (Toleikyte et al., 2016).

The main benefits of the measures mentioned by the applicants were lower costs for electricity and heating and increased thermal comfort after implementation of the measures. The applicants reported significantly lower energy bills and in some cases even the fact that in their apartments, they did not even need to heat most of the rooms in winter. The applicants further enjoyed the increased usage comfort, especially when exchanging the old coal boilers for new, automated biomass boilers, which do not need to be filled for several days.

Several applicants complained that after insulation of the buildings, they detected mold in the buildings. It is caused by improper use of the newly insulated houses, especially lack of regular ventilation of the space. The suppliers may not have correctly instructed the users in this sense.

The applicants were asked, whether they would implement the energy efficiency measures even without the subsidy. From the 13 replies, six respondents would do the measures even without subsidy (insulation, low-energy house, solar thermal systems and biomass boiler). In five cases, the applicants said that without subsidy, they would carry out only part of the measures (leaving out mainly solar-thermal systems) or implemented it differently (thinner insulation of a building, natural gas instead of heat pump). Two respondents would not implement the measures at all without a subsidy (both for solar-thermal systems). Even though the sample of respondents is rather small in this case, it shows that the program rightly supports either the “new” technologies or more complex solutions, such as solar-thermal systems, combinations of measures, and higher quality of the measures (thicker insulation).

In several cases, the applicants mentioned the principal-agent problem[4] hindering implementation of energy efficiency measures in their buildings. One multi-apartment building owner asserted he would not benefit directly from the energy efficiency measures. However, he added that he would still implement the measures, as he expects they will increase the market value of the building and the apartments.

The slightly different view is the one in the multi-apartment buildings, where the users own each apartment and altogether the multi-apartment building is managed by the homeowner's associations and condominiums. In such case, the body authorized to implement the measures—the elected committee of the building complained it was somewhat difficult to persuade all the owners who need to give their consent to carry out the project. It seemed that most owners were unable to foresee the benefits of the measures, including both lower energy bills, increased comfort, and higher market price of their property. One applicant was so disappointed with the whole process; he claimed that they would consider rather carefully if they were to undergo the whole process again. On the other hand, another building owner asserted, that once implemented, the project served as an inspiration for surrounding houses that followed the example and realized similar measures, too.

6 | CONCLUSION

The Energy Efficiency Directive (European Parliament and Council, 2012) is a strong instrument to attain the EU long-term targets on energy savings and GHG emission reduction. The assumption that lower energy consumption will lead to the decrease of energy poverty, decrease of energy sources dependency and increase of energy security is a crucial argument. The highest energy saving potential lies in the renovation of existing buildings. One of the most powerful parts of the Directive is the Article 7, which aims at achieving new savings of 1.5% each year by 2020.

The Green Savings Programme represents one of the most important instruments of the alternative scheme applied in the Czech Republic within Article 7 of the Directive. It also remains one of the biggest energy efficiency programs for households in Europe, as over 150,000 households were involved. Implementation of the Green Savings Programme has shown that this program has been a new impetus for the development of further energy efficiency projects in the field of residential buildings. The Programme led to an immediate CO_2 emission reduction and kick-started a long-term trend of sustainable construction.

In total, 206 measures were inspected in 124 projects, including combinations of measures. The comparison of ex ante and ex post CO_2 emission reduction could be performed at 70 projects (56% success rate). In case the ex post calculation could not be made, the reasons were mostly the unavailability of invoices, low level of detail or the fact that the buildings were not inhabited yet or for a sufficient amount of time (in case of new buildings).

The inspections showed that there is a significant difference between the ex ante CO_2 emission reduction and ex post results (25% on average). The reasons are partly methodical (e.g., calculation methods and norms used for calculation of specific heat demand, inability to cover other heat sources such as fireplaces), but most can be attributed to the behavioral factors in the respective buildings. Higher thermal comfort than in the ex ante calculations leads to lower real savings. Similarly, occupancy or patterns of use of the buildings have a high impact on resulting savings. If the buildings are not fully used for long-term, the measures have highly lower positive impact.

The paper demonstrates that the ex post evaluation should be a standard part of the energy efficiency program. Even if the supported projects are small (family houses or building technologies), a sample of applications (units of percent of the whole population) should be selected where the ex post evaluation would be carried out. Importantly, such research should be independent of the inspections implemented for legal requirements (avoiding deceptions). Only in such case, there can be a useful cooperation between the building owners and the research team.

The results of the paper open the relationship between calculated and measured savings. As only calculated savings are available before the project implementation, it is necessary to keep it. However, the measured savings are those used in the national energy balance and targets set up according to Article 7 of Energy Efficiency Directive (European Parliament and Council, 2012). It means that rules or calculations taking into account behavior of the building user could be set up.

A significant amount of financing has been available under the GIS in the Czech Republic. However, the results of our research have confirmed that careful evaluation of the supported projects is needed to optimize the programs and to see the actual effects of the program. In reality, the follow-up program, the New Green Savings Programme running since 2013 involves significantly lower number of households (around 14,000 as of 2018). The program setting does not envisage any changes regarding ex post evaluation.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the financial support for the research that led to this paper that was provided by the grant no. TJ01000066 by the Technology Agency of the Czech Republic. Special thanks are expressed to SEVEn, The Energy Efficiency Center, for cooperation on the project.

CONFLICT OF INTEREST

The authors have declared no conflicts of interest for this article.

ENDNOTES

[1]Large-scale projects tend to include ex post evaluation as one of the most important evaluation indicators (Honzík, Karásek, & Chmel, 2014).

[2]The greening ratio indicator (GI) is a nonunit quantity that expresses the effectiveness of funds used from sales of AAU in reducing CO_2 emissions. It may be expressed as a ratio of 1 toward the ratio of sold and reduced CO_2 emissions. The value of GI may be obtained through the ratio of the investment support in Euros and a multiplication of the price per sold AAU unit and the amount of reduced emissions expressed in tons of $CO_{2\text{-eq}}$.

[3]We did not perform any climatic transformations as their influence compared to the behavioral aspects is small. Moreover, the paper compares projects from various climatic zones and different years of project implementation and consumption data collection.

[4]The principal-agent problem means a barrier of split incentives (Jochem & Gruber, 1990). The owners of the building have the incentive to invest in the efficiency measure. However, they do not control the use of the efficient equipment and the efficiency gains. The owner also does not receive the benefits of the measure—the tenant pays lower energy bills. Conversely, the user has little incentive to invest, as there is high uncertainty as to length of the contract (Valentová, 2010).

REFERENCES

Carley, S., & Browne, T. R. (2013). Innovative US energy policy: A review of states' policy experiences. *WIREs Energy and Environment*, *2*, 488–506. https://doi.org/10.1002/wene.58

Clinch, J. P., & Healy, J. D. (2001). Cost-benefit analysis of domestic energy efficiency. *Energy Policy*, *29*, 113–124. https://doi.org/10.1016/S0301-4215(00)00110-5

European Commission. (2016). *Annex Accelerating clean energy in buildings to the communication from the commission to the European parliament* (No. COM(2016) 860 final). The Council, the European Economic and Social Committee, The Committee of the Regions and the European Investment Bank Clean Energy for all Europeans.

European Parliament and Council. (2012). *Directive 2012/27/EU of the European Parliament and of the Council of October 25, 2012 on Energy Efficiency, amending directives 2009/125/EC and 2010/30/EU and repealing directives 2004/8/EC and 2006/32/EC*. Official Journal of the European Union L315/1.

Honzík, M., Karásek, J., & Chmel, P. (2014). *Basis for the national action plan for Ministry of Industry and Trade*. Prague, The Czech Republic: SEVEn.

Jochem, E., & Gruber, E. (1990). Obstacles to rational electricity use and measures to alleviate them. *Energy Policy*, *18*, 340–350. https://doi.org/10.1016/0301-4215(90)90192-7

Karásek, J. (2011). *Results of the Green investment scheme.* Paper presented at the Seminar of Japanese Clean Technologies. Prague, The Czech Republic.

Karásek, J., & Pavlica, J. (2016). Green investment scheme: Experience and results in the Czech Republic. *Energy Policy*, *90*, 121–130. https://doi.org/10.1016/j.enpol.2015.12.020

Le Den, X., Riviere, M., Lessman, F., Nesbit, M., Paquel, K., & Illes, A. (2016). *Evaluating EU cohesion policy funding for energy efficiency Investments in Public and Residential Buildings across EU member states.* Paper presented at the International Energy Policies & Programmes Evaluation Conference, Amsterdam, The Netherlands.

Ministry of Industry and Trade of the Czech Republic. (2004). VYHLÁŠKA ze dne 29. června 2004, kterou se mění vyhláška č. 213/2001 Sb., kterou se vydávají podrobnosti náležitostí energetického auditu (Decree on which details are issued for particulars of the energy audit).
Ministry of Industry and Trade of the Czech Republic. (2013). Vyhláška č. 78/2013 Sb. o energetické náročnosti budov (Decree on energy performance of buildings).
Sayeg, P., & Bray, D. (2012). Estimating changes in emissions from bus rapid transit: Making best use of transport sector experience: Estimating changes in emissions from bus rapid transit. *WIREs Energy and Environment*, *1*, 308–316. https://doi.org/10.1002/wene.27
State Environmental Fund. (2014). Výroční zpráva programu Zelená úsporám za rok 2013 (Annual report of the Green Savings Programme 2013).
Toleikyte, A., Kranzl, L., Bointner, R., Bean, F., De Groote, M., Hermelink, A., …, Volt, J. (2016). *ZEBRA 2020 - Nearly zero-energy building strategy 2020. Strategies for a nearly Zero-Energy Building market transition in the European Union.* Zebra 2020.
Valentová, M. (2010). Barriers to energy efficiency – Focus on transaction costs. *Acta Polytechnica*, *50*(4), 87–93. https://doi.org/10.14311/1247
Webber, P., Gouldson, A., & Kerr, N. (2015). The impacts of household retrofit and domestic energy efficiency schemes: A large scale, ex post evaluation. *Energy Policy*, *84*, 35–43. https://doi.org/10.1016/j.enpol.2015.04.020

How to cite this article: Valentová M, Karásek J, Knápek J. Ex post evaluation of energy efficiency programs: Case study of Czech Green Investment Scheme. *WIREs Energy Environ*. 2018;e323. https://doi.org/10.1002/wene.323