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ANALYZING THE EFFECTS OF A RENEWABLE ENERGY SUPPORT MECHANISM ON INVESTMENTS UNDER UNCERTAINTY: CASE OF RUSSIA

Thesis for the degree of Doctor of Science (Economics and Business Administration) to be presented with due permission for public examination and criticism in the Auditorium 4301-4302 at Lappeenranta University of Technology, Lappeenranta, Finland on the 12th of December, 2017, at noon.

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Abstract

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More and more countries worldwide introduce renewable energy policies to incentivize new investments. This trend is followed by a growing body of academic research that intends to assess the effectiveness of different support mechanisms in promoting renewable energy. Russia has recently introduced a support mechanism for renewable energy investments that considerably differs from existing, widely spread, types of support mechanisms. However, the design of the Russian mechanism has received only modest attention in the academic and the business literature. The main purpose of this research is to analyze the effects of the Russian renewable energy support mechanism on investment profitability. This thesis is a collection of publications linked by a common theme of studying renewable energy profitability under the Russian support mechanism.

In the efforts to analyze the Russian renewable energy support mechanism, this research applies several investment analysis techniques, including traditional capital budgeting analysis, sensitivity analysis, simulation-based and fuzzy set theory-based real options approaches. To enhance the information content and analytical power of the simulation-based real options approach, this research introduces a new and improved investment analysis method that is able to capture the complexity of investments with multivariable uncertainty and that facilitates decision-making.

The results of this thesis provide a holistic picture of the Russian renewable energy support mechanism on investment profitability. It is noted that the mechanism shields investment profitability from the changing market environment and incentivizes the high performance of renewable energy projects. The contributions of this research include the creation of a roadmap for investors and project managers planning renewable power generation projects in Russia, providing insight for researchers and policymakers on alternative to the mainstream designs for renewable energy support, and presenting the new simulation-based method for investment analysis for better decision making. The applicability of the new method can be generalized into broader investment valuation context, independent of a particular industry.

Keywords: renewable energy, Russia, investment analysis, real options

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Mariia Kozlova
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Taipalsaari, Finland

Contents

List of publications

I. Kozlova M. and Collan M. (2016). Modeling the effects of the new Russian capacity mechanism on renewable energy investments. *Energy Policy*, 95, pp. 350-360.

II. Kozlova M. (2017). Real option valuation in renewable energy literature: research focus, trends and design. *Renewable and Sustainable energy reviews, 80*, pp. 180-196.

III. Kozlova M., Collan M., and Luukka P. (2018). Russian Mechanism to Support Renewable Energy Investments: Before and After Analysis. *Computational Methods and Models for Transport - New Challenges for the Greening of Transport Systems,* Springer. pp.243-252.

IV. Kozlova M., Collan M., and Luukka P. (2015). Renewable Energy in Emerging Economies: Shortly Analyzing the Russian Incentive Mechanisms for Renewable Energy Investments. *Proceedings from International Research Conference 'GSOM Emerging Markets Conference-2015: Business and Government Perspectives', Saint-Petersburg, Russia*

V. Kozlova M., Collan M., and Luukka P. (2016). Comparison of the Datar-Mathews Method and the Fuzzy Pay-Off Method through Numerical Results. *Advances in Decision Sciences*, vol. 2016, p.7.

VI. Kozlova M., Collan M., and Luukka P. (2016). Simulation decomposition: new approach for better simulation analysis of multi-variable investment projects. *Fuzzy Economic Review*, 21(2), p.3.

Mariia Kozlova is the principal author and investigator of all papers included in this dissertation. She is also the corresponding author for all included publications.

List of abbreviations

CapEx	capital expenses
DMM	Datar-Mathew method
FiT	feed-in tariff
FPOM	fuzzy pay-off method
GW	gigawatt
MW	megawatt
MWh	megawatt hour
NPV	net present value
OpEx	operational expenses
PV	photovoltaic
RE	renewable energy
REN21	Renewable Energy Policy Network for the 21st Century
RO	real option
ROA	real options approach
RQ	research question
UNEP	United Nations Environmental Program
WACC	weighted average cost of capital

1. Introduction

1.1. Context and motivation

In order to reduce carbon emissions, pursuing independent energy supply and economic development, governments worldwide have adopted renewable energy (RE) policies to promote RE investments. According to global industry reviews, 173 countries have established RE targets and 146 countries have had RE support mechanisms in place by the end 2015 (REN21, 2016). Mostly due to supporting policies, global new investment in RE reached its highest level of 286 billion dollars in 2015 and for the first time developing countries were leading the investments (Frankfurt School UNEP Collaborating Centre & Bloomberg New Energy Finance, 2016).

1.1.1. RE policy worldwide

This trend has also found resonance in academia, where researchers strive to analyze and optimize RE support mechanism designs, in order to find a compromise between effective promotion of RE investments and the overall burden to taxpayers. Common, widely spread, types of RE support mechanism designs to incentivize industrial-scale investments include the “feed-in tariff” (FiT) and premium programs, “tendering schemes”, and “trading mechanisms”, such as RE certificate trading, and renewable portfolio standards (REN21, 2016). All these different designs provide remuneration (support) to RE investments per unit of electricity produced. This, per unit of electricity produced basis, is a “natural” choice, because the electricity production of RE power plants is typically intermittent.

RE support policy research embraces a variety of targets, countries, and approaches. Typically, researchers have analyzed how RE support mechanisms affect the uncertainty surrounding RE investments and hence their efficiency in promoting RE investments (Eryilmaz & Homans, 2016; Kumbaroğlu, Madlener, & Demirel, 2008; Lin & Wesseh Jr, 2013; Wesseh & Lin, 2016; Yu, Sheblé, Lopes, & Matos, 2006; Zhang, Zhou, & Zhou, 2014). Some studies have gone further and seek to optimize RE support mechanism parameters (Jeon, Lee, & Shin, 2015; K. Kim & Lee, 2012; Ritzenhofen & Spinler, 2016; Zhang, Zhou, Zhou, & Liu, 2016).

One well-trodden path of RE policy research is to comparatively analyze the existing RE support mechanisms. Such studies shed light on the relative effectiveness of the different mechanisms in promoting RE and allow deeper understanding of RE policy effects on RE investments. Typically, FiT schemes and RE certificate trading mechanism have been compared (Boomsma & Linnerud, 2015; Boomsma, Meade, & Fleten, 2012; Kitzing, Juul, Drud, & Boomsma, 2017; Scatasta & Mennel, 2009). The general conclusion from the research is that FiT, by providing a fixed certain (non-risky) compensation per unit of electricity produced, encourages fast investment, whereas the uncertain price of RE certificates creates more incentives for bigger investments, in case of expected favorable future (RE certificate) price development. The above research, alongside other RE policy research, e.g., (Eryilmaz & Homans, 2016; Fuss, Johansson, Szolgayova, & Obersteiner, 2009; Ritzenhofen & Spinler, 2016), also highlight the effects of policy uncertainty and the possibility of retroactive changes on RE investment support, in slowing down RE investments and on the effectiveness of RE support mechanisms.

RE policy examples that enable operational flexibility for RE investments deserve separate attention. One such a mechanism is in place in Spain and provides RE project managers with a choice of whether to sell electricity at a fixed FiT rate, or at a premium over the volatile electricity market price – the choice is made periodically. Researchers who have studied this policy (Balibrea-Iniesta, Sánchez-Soliño, & Lara-Galera, 2015; Yu et al., 2006) argue that such a regulatory real option increases the expected project value and reduces investment risk exposure.

Although RE supporting policy research is diverse in terms of specific objectives and methodologies, the overall raison d´être can be characterized as a "quest for the ideal RE support mechanism" in terms of RE investment promotion.

1.1.2. RE policy in Russia

Typically, emerging economies seeking to introduce RE support mechanisms have adopted one of the pre-existing RE support designs. In contrast, Russia has recently implemented a RE support scheme, based on local energy system trading rules that is designed to compensate RE investors not for the electricity produced, but for the capacity installed (Government of Russian Federation, 2013a). Known in the English language literature as the (Russian) RE capacity mechanism, it represents a unique approach to support RE investments that is considerably different from other existing RE support schemes.

So far the Russian RE capacity mechanism has received modest attention in both business and in scientific literature and is limited to only a few qualitative analyses (Boute, 2015; Boute, 2012; International Finance Corporation, 2013; Smeets, 2017) and a (single) study of its impact on market prices (Vasileva, Viljainen, Sulamaa, & Kuleshov, 2015). Therefore, studying the design of the Russian capacity mechanism is of value, not only for the actors related to the Russian energy markets, but for the RE community in general, and especially for researchers and for policymakers engaged in designing and studying RE support schemes.

1.1.3. Approaches to study RE policies

To shed light on RE mechanism effects on RE investments, and to compare different designs, researchers naturally use numerical studies. An early review of the field by Menegaki (Menegaki, 2008), shows that researchers have applied many different valuation methods to renewable energy investments. These include, e.g., the "levelized cost of electricity" indicator, classical capital budgeting techniques, and real option (RO) analysis. Later, Fernandez et al. (2011) highlighted the advantages of RO analysis over other appraisal techniques, in light of the uncertainty associated with RE investments and their capital intensity. Recent trends show an increased volume of scientific research that addresses RE investment analysis with RO methods (Martínez Ceseña, Mutale, & Rivas-Dávalos, 2013).

It must be noted that a variety of possible methods exists also within real option analysis. When researchers' target is to estimate optimal investment timing, under a given support mechanism, they generally use partial differential equation based methods and apply a dynamic programming optimization procedure (Boomsma & Linnerud, 2015; Kitzing et al., 2017; Kumbaroğlu et al., 2008; Scatasta & Mennel, 2009). Binomial trees, or lattices, are generally used, when researchers identify a set of compound real options, such as the RO to continue, or to abandon (Lee & Shih, 2011; Lin & Wesseh Jr, 2013; Zhang et al., 2014). Monte Carlo simulation-based RO methods are typically employed for general assessment of support mechanisms and their effect on uncertainty associated with RE investments (Balibrea-Iniesta et al., 2015; Iniesta & Barroso, 2015; Yu et al., 2006). Fuzzy set theory-based methods that are able to capture the imprecision in (expert) estimates, are also emerging in RE studies (Sheen, 2014).

Although the choice of the RO method used should generally be connected to a particular problem setting, the objectives of the study, and the type of uncertainty faced (Collan, Haahtela, & Kyläheiko, 2016), the application of more than one RO technique to study the same case can bring additional insight.

1.1.4. This research

The first objective of this research is to analyze the effects of the Russian RE support mechanism on RE investments. This will provide an understanding of this Russian alternative to the more widely spread designs for RE support mechanism, of the efficiency of the Russian mechanism in RE promotion, and of the cost-effectiveness of the Russian RE support mechanism. To better explore the mechanism´s effects, several investment models have been built as a part of this research. Models have been built by using the classical structure of the discounted cash-flow based capital budgeting techniques (spread sheet), by using simulation-based modeling methodology, and by employing a fuzzy set theory-based approach. To provide a solid background for the research design, an extensive academic literature review has been conducted on the use of real option approaches in RE investment valuation.

Several parameters of the Russian RE support mechanism shape the profitability of a RE investment in a stepwise manner. This means that understanding the mechanism completely requires understanding the effect of each parameter separately. For this purpose, in this research, a detailed simulation model, reproducing the mechanism architecture, was built to analyze the effects of each parameter. From this model and from the study of the effect of each mechanism parameter to the end result grew the idea to *construct a methodology that generally improves the understandability of the relationship between parameters and the end result in multi variable simulations. Putting this idea into practice became the second objective of this research.*

A practical contribution of this research is (the first) detailed English language presentation and analysis of the Russian RE support mechanism that is of value to a number of different stakeholders in the RE industry that include policy makers, investors, and project managers. The scientific contributions of this research include (i) the examination of the effects of the new Russian RE support mechanism on the profitability of new investments initiated under the mechanism; (ii) the demonstration of the applicability of the existing RO methods to the analysis of this mechanism; and (iii) the development and testing of a new generic method to complement simulation-based multi-variable (investment) analysis. These results will benefit the scientific community related to RE economics and the practice of investment valuation in general.

1.2. Focus of the research

The focus of this research can be illustrated as the intersection of the underlying themes, namely ‘Renewable energy’, ‘Russian support mechanism’, and ‘Investment analysis’ as presented in Figure 1.

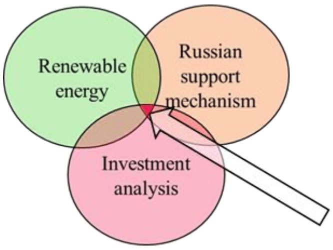

Figure 1. Focus of the research

This research falls into the domain of renewable energy, specifically focusing on the new Russian RE support mechanism. Another chosen domain is investment analysis, because its application can shed light on the mechanism efficiency in promoting RE investments.

1.3. Research objectives and questions

As already mentioned above, this research has two main objectives:

<u>Objective #1.</u> To gain a better understanding of the effects of the Russian RE support mechanism on RE investments.

To meet the first research objective, this work seeks to answer the following specific research question (RQ) and sub-questions:

RQ #1. How does the Russian RE support mechanism affect RE investment profitability?

RQ #1.1. What is the detailed design of the Russian RE support mechanism and what is the procedure used in the remuneration calculation?

RQ #1.2. What are the key drivers of profitability for Russian RE investments under the new RE support mechanism?

RQ #1.3. What insights do RO valuation techniques bring to the Russian RE support mechanism analysis?

Objective #2. To create new and better profitability analysis tools that provide better decision-support for investments, such as investments in RE in the Russian context studied here.

To fulfill the second objective this research concentrates on studying and researching further simulation and fuzzy logic-based real option methods.

> RQ #2. Can (the existing simulation and fuzzy logic-based) real option methods be enhanced to deliver more / better information for decision-making?
>
> > RQ #2.1. What shortcomings of these methods can be identified?
> >
> > RQ #2.2. Can the shortcomings of these methods be resolved?

1.4. Outline of the thesis

This thesis is based on a collection of articles. Seven chapters of the thesis develop the common theme that ties together the six enclosed publications, Figure 2.

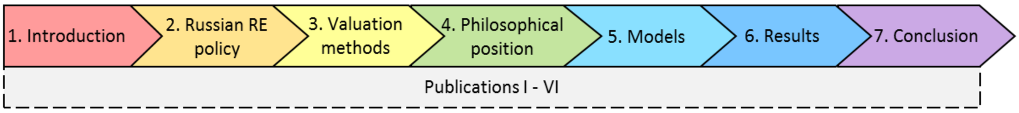

Figure 2. Structure of the thesis

Following this introduction, chapter two provides an overview of the Russian RE policy and its RE support mechanism, as well as, the coverage of this theme in academic and business literature. Chapter three delivers the basics of the employed valuation methods and the rationale behind using them. The philosophical position of the research is presented in chapter four. Chapter five describes the models constructed within this research and illustrates how the particular methods were implemented, in the context of the Russian RE support mechanism. Chapter six summarizes the main findings of the publications. Finally, chapter seven is devoted to discussion and conclusions, in particular to answering the research questions, emphasizing the scientific and practical contributions of the research, discussing the limitations of this research, and to providing further research directions.

Essentially, the introduction, the philosophical position of the research and the conclusion parts concern all of the research questions. The second and third chapters provide a case-specific and methodological background for the research question #1. The models described in chapter five act as partial answers to the applicable research questions. The general profitability model is built to define key profitability drivers of RE investments under the Russian support mechanism (RQ #1.2). Monte Carlo simulation and pay-off models employ RO approach (RQ # 1.3) and are used to analyze and compare the performance and the information content of the methods (RQ #2.1). The description of the extended simulation model is connected to RQ #2.2.

Table 1 illustrates the connection and the contribution of the chapters and the included publications towards the research questions.

Table 1. Research questions in the thesis structure

Thesis chapters	**RQ #1** *How does the Russian RE support mechanism affect RE investment profitability?*			**RQ #2** *Can RO analysis methods be enhanced to deliver more information for decision-making?*	
	RQ #1.1 *(design of the mechanism)*	RQ #1.2 *(key profitability drivers)*	RQ #1.3 *(insights from RO approach)*	RQ #2.1 *(cons of the methods)*	RQ #2.2 *(resolving the cons)*
1. Introduction	▨	▨	▨	▨	▨
2. Russian RE policy	▨				
3. Valuation methods	▨	▨			
4. Philosophical position of the research	▨	▨	▨	▨	▨
5. Constructed models within this research					
5.1. General profitability model		▨			
5.2. Monte Carlo simulation model			▨	▨	
5.3. Extension of the simulation model					▨
5.4. Pay-off method implementation			▨	▨	
6. The publications and summary of the results					
6.1. Publication I	🟩	🟩			
6.2. Publication II			🟩		
6.3. Publication III	🟩	🟩	🟩		
6.4. Publication IV	🟩	🟩	🟩		
6.5. Publication V				🟩	
6.6. Publication VI		🟩	🟩		🟩
7. Discussion and conclusion	▨	▨	▨	▨	▨

Publications I, III, and IV are case oriented and contribute to the RQ #1. Publication I presents the results of the general profitability model. Publication II sheds light on the existing RO approaches in RE valuation. Publications III and IV further study the Russian RE support mechanism by the RO approaches, the simulation-based and the fuzzy set theory-based methods, correspondingly. Publication V compares the aforementioned methods (RQ #2.1). Finally, Publication VI presents a new extension of the simulation-based method (RQ # 2.2) that is used to provide additional decision-making insight into the Russian RE support mechanism effects (RQ # 1.2&1.3).

2. Russian RE policy

Instead of adapting one of the existing widespread RE support designs, Russia has introduced a unique RE support mechanism, the origin of which lies in the pre-existing Russian energy market capacity trading rules. According to these rules, new planned investments into conventional power generation, such as investments into coal and gas plants that have been selected via a capacity auction, are entitled to long-term capacity delivery contracts (Boute, 2012). These capacity contracts provide revenue, in addition to electricity sales that ensures the profitability of these investments. Being a part of the overall capacity trading system of the Russian energy market, such a mechanism aims to create a secure long-term energy supply for Russia. Selling capacity means in practice that the plant is available to produce electricity, while purchasing capacity can be understood as buying a right to be supplied with electricity. All industrial agents on the Russian wholesale energy market are subjected to capacity trade. Such electricity market design is not unique, also other countries, seeking to enhance reliability of energy systems, have implemented capacity markets and other capacity mechanisms (Held & Voss, 2013; Hobbs, Hu, Iñón, Stoft, & Bhavaraju, 2007; Tennbakk et al., 2013), but never before has a capacity mechanism design been used to support RE investments.

The Russian RE support mechanism has received modest attention in the English academic and business literature, likely due to it having been only recently implemented. A general description and a qualitative analysis of the scheme can be found in (Boute, 2015; Boute, 2012; International Finance Corporation, 2013; Smeets, 2017). At this time a single quantitative study exists that aims to uncover the impact of the mechanism on market electricity and capacity prices (Vasileva et al., 2015). To the best of our knowledge, the publications from this research, offer for the first time a deeper numerical analysis of the Russian RE support mechanism effects on RE investment profitability.

The Russian *capacity mechanism for RE aims to provide a risk-free return for RE investments* (Government of Russian Federation, 2013a; Government of Russian Federation, 2013b). Annually conducted RE capacity auctions select projects with the least planned capital costs. The selected projects from these auctions get long-term capacity agreements that come into force after project commercialization. Capacity payments within these agreements are recalculated on an annual basis, taking into account project-specific factors and changes in the market conditions, Figure 3.

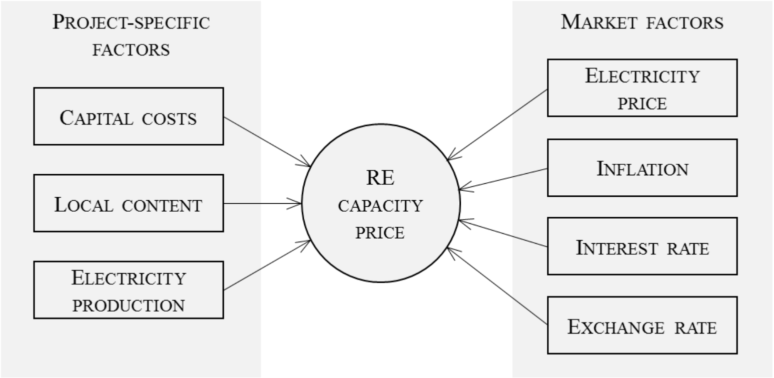

Figure 3. Factors affecting RE capacity price formation

Periodic *recalculation of the RE capacity price* is done in order to offset (adapt to) the influence of changes in market conditions during the capacity agreement term. The capacity mechanism sets targets and requirements (levels) for project specific factors and penalizes RE investments, by decreasing capacity price remuneration, in cases of non-compliance. *Capital costs limits* are imposed for different technologies specifically (wind, solar, hydro) and limits are year-specific. *A local content requirement*, or the request / necessity to acquire locally produced equipment and services, is also set specifically for each technology type and for each year of commercialization. Projects with capital costs that are higher than the aforementioned capital costs limits, or that do not meet the local content requirements, are dropped out of the first round of the capacity auction. Projects that comply with the requirements and are selected in the auction, but underperform these requirements during the construction phase, end up with lower capacity prices. The mechanism sets three levels of average annual capacity factors for *electricity production*, each level associated with a specific capacity price, “full remuneration” is paid for investments that reach the highest level. The overall capacity price calculation procedure resembles the calculation of an annuity, with variable interest rates that are adjusted by a number of coefficients. According to the statement of a Russian policy expert, it took about two months for a group of law specialists and economists to implement this calculation procedure. It is presented step by step in Publication I, with all mechanism requirement details included.

The total amount of RE capacity to be auctioned is defined centrally for each year and accounts for a total of more than 5 GW by 2020. Three types of RE technology are included in the support scheme, specifically wind, solar PV, and small (less than 25 MW) hydropower.

3. Valuation methods

Conventional investment valuation techniques find their roots in the discounted cash-flow (DCF) concept (Fisher, 1907; Marx, 1894). It is a basis for classical capital budgeting analysis, commonly employed in business (Graham & Harvey, 2001). Discounted cash-flow analysis, however, provides limited grounds for decision-making due to the assumption of certain and deterministic nature of future cash-flows. Possible supplementary methods, such as sensitivity, or scenario analysis, allow the derivation of a broader picture, but still remain limited in capturing uncertainty surrounding investment projects. Sensitivity analysis offers the possibility to study the uncertainty affecting a “system” factor by factor, but does not consider the joint effect of the factors, whereas scenario analysis results are determined by custom-made assumptions on possible combinations of discrete states of uncertain factors. Both methods do not necessarily reveal sources of *managerial flexibility* that can be of value for investment projects.

The real options approach (ROA) has been gradually spreading into corporate investment valuation practices (Block, 2007; Graham & Harvey, 2001; Ryan & Ryan, 2002). The rationale behind ROA is that the approach, in contrast to classical capital budgeting analysis, allows the incorporation of uncertainty effects and captures the value of flexibility (Amram & Kulatilaka, 1998; Trigeorgis, 1995). Historically, the ROA arises from financial theory by adopting the Black-Scholes model (F. Black & Scholes, 1973) originally created for financial option pricing to the valuation of real options. Later, the binomial tree model was introduced (Cox, Ross, & Rubinstein, 1979) and was also adopted to the valuation of real options. The binomial model has also been used in recent studies (Gray, Arabshahi, Lamassoure, Okino, & Andringa, 2005; B. Kim, Lim, Kim, & Hong, 2012; MacDougall, 2015). Nowadays, a variety of RO methods exist and are based on different theoretical backgrounds (Trigeorgis, 1996), offering real option analysis users to choose also between Monte Carlo simulation-based (Boomsma et al., 2012; Datar & Mathews, 2004; Mathews, Datar, & Johnson, 2007; Monjas-Barroso & Balibrea-Iniesta, 2013), fuzzy set theory-based (Allenotor, 2011; Carlsson & Fullér, 2011; Collan, 2011; Collan, Fullér, & Mezei, 2009; Hassanzadeh, Collan, & Modarres, 2012; Sheen, 2014) and system dynamics-based modeling of real options (Johnson, Taylor, & Ford, 2006; O'Regan & Moles, 2001; Sontamino & Drebenstedt, 2014; Tan, Anderson, Dyer, & Parker, 2010). The selection of the used ROA should be based on the objectives of the research, the problem setup, and on the available information, which is typically determined by the type of uncertainty that the problem faces.

For the purposes of this research, two similar in the valuation logic, but different in theoretical foundations, RO methods are chosen: the Datar-Mathews method, based on Monte Carlo simulation, and the fuzzy pay-off method for real option valuation, based on fuzzy set theory. Both methods are shortly presented in the following subsections. These methods can handle the type of uncertainty prevalent in the studied problem and thus are suitable for the analyses conducted.

3.1. Datar-Mathews method based on Monte Carlo simulation

The Datar-Mathews method (DMM) captures uncertainty associated with investments by means of Monte Carlo simulation (Mathews et al., 2007). A classical capital budgeting model based on a net present value (NPV) calculation and NPV as the outcome functions as the underlying model for the simulation. The uncertainty in the input variables is estimated, in order to create a distribution of project cash-flows with the Monte Carlo simulation. The whole project is treated as a real option, this can be understood as an analysis to support decision-making in terms of “invest or wait”. The connection context is that the method is used to study under which circumstances (considering the Russian RE support mechanism) the option to invest in an RE plant in Russia should be exercised. The RO value is calculated as a risk adjusted weighted mean of the positive part of the NPV distribution, Figure 4.

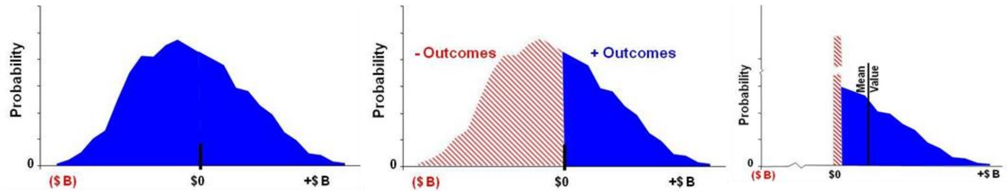

Figure 4. Datar-Mathews method: NPV distribution (left), mapping weights of the negative part of the distribution to zero (middle), calculating RO value as a mean of the positive part of the distribution (right)

In other words, the RO value can be formulated as (Mathews et al., 2007):

‘RO value = Risk Adjusted Success Probability * (Benefits – Costs)’ (1)

The DDM has previously been used, e.g., in the aircraft industry (Mathews & Salmon, 2007; Mathews, 2009; Mathews et al., 2007) and health care technologies (Lall, Lowe, Goebel, & Cooper, 2012). Here the application space is extended to renewable energy.

3.2. Fuzzy pay-off method for real option valuation

The fuzzy pay-off method for real option valuation (FPOM) also utilizes the classical DCF valuation model as a basis (Collan et al., 2009). The method is based on asking “managers” to estimate three (or more) cash-flow scenarios, based on their perceived uncertainty of the input variables. A fuzzy NPV distribution, also called the fuzzy project pay-off distribution, is constructed by using NPV derived from the three (or more) given cash-flow scenarios as a fuzzy number. The extreme (minimum and maximum) scenario NPVs represent the limits of the fuzzy NPV distribution. The fuzzy NPV distribution is treated as a fuzzy number. The construction of a fuzzy NPV distribution from scenarios is explained in detail in (Collan et al., 2009). A three-scenario case is illustrated on Figure 5.

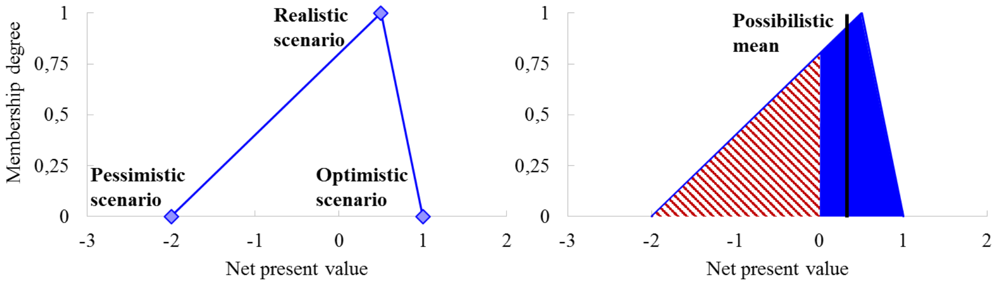

Figure 5. Pay-off method: building a fuzzy NPV distribution (left), calculating RO value from the possibilistic mean of the positive part of the distribution (right), weighted by the project success-ratio

As the fuzzy NPV is considered to be a (normal) fuzzy number, the y-axis depicts the degree of membership of a given NPV to the fuzzy NPV distribution (fuzzy number). It must be observed that the fuzzy NPV distribution is not a probability distribution, as the NPV distribution resulting from the Monte Carlo simulation used in the Datar-Mathews method. The real option value is defined as the success-ratio (area over positive NPV part of the distribution / total area of the distribution) weighted mean of the positive part of the distribution:

‘RO value = Possibilistic mean of the positive area * positive area / whole area’ (2)

The fuzzy pay-off method for real option valuation has been used to deal with various decision making problems, including R&D project selection (Bednyagin & Gnansounou, 2011; Hassanzadeh et al., 2012), economic feasibility analysis of giga-investments (Collan, 2011; Kozlova, Collan, & Luukka, 2015), and patent valuation (Collan & Heikkilä, 2011).

4. Philosophical position of the research

4.1. On modeling as a methodology framework

Modeling is one of the ways to study the nature of reality (Swoyer, 1991). The well-established notion of scientific models interprets them as a stylized, or a simplified, representation of target real systems (M. Black, 1962). Essentially this means that there can be different model representations of the same real system. Thus there are no “right” or “wrong” models, the metric used rather is how useful different models are in creating an understanding of the real system depicted, in a specific context and with regards to the objectives of the modeling endeavor. As a philosopher Paul Teller wrote, “*the only PERFECT model of the world, perfect in every little detail, is, of course, the world itself*” (Teller, 2001). This discussion is not new, in fact, the notion of requisite variety (Ashby, 1991) infers that the complexity of a model should reflect the complexity of the real world situation modeled if it is hoped that a “life-like” complexity is captured. In terms of this research this means that all the complexity of the studied RE support mechanism should be included in the model.

When the applicability and usefulness of a model is studied, its validation vis-à-vis the real world plays an important role. Approaching this issue, Mitroff and others (Mitroff, Betz, Pondy, & Sagasti, 1974) propose a systemic view of problem solving in operations management research, Figure 6.

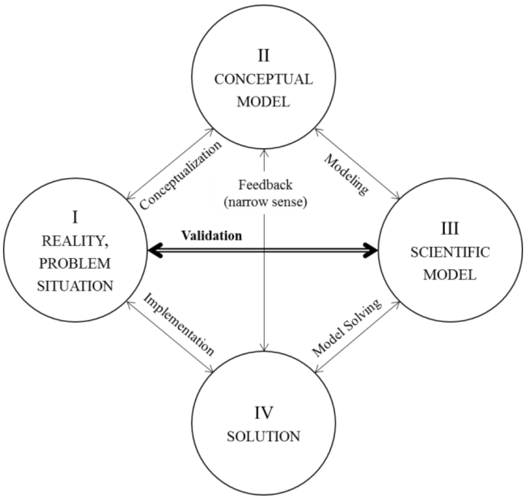

Figure 6. System view on problem solving (Mitroff et al., 1974)

This systemic problem solving view is taken as a methodological framework of this study. The roots of this research lie in the identification of the investigated real-world problem (and research gap) (point I) that is, the new Russian RE support mechanism design. Investigation and analysis of the detailed structure of the support mechanism, as well as the inquiry to the state-of-the-art RE policy research cover the point II “conceptual model” of the framework.

Construction and application of a variety of models in studying the effects of the RE support mechanism (point III) illustrate how the mechanism functions (point IV). Results from the models and simulations have been iteratively validated by emerging evidence from the real-world implementation of the mechanism in Russia (link from III to I).

4.2. On uncertainty and imprecision

Investment modeling is generally a forward looking exercise and naturally associated with future uncertainty and imprecision of estimates. Lawson (1988) distinguished two types of uncertainty in economic analysis. The first one is associated with a subjectivist view on probability, where distributional parameters depend on subjective knowledge, or belief. The second type interprets probability as a property of material reality, where parameters of the probability distribution are “objective” and can be extracted from, e.g., historical data. In this research, both types of uncertainty can be found. External market-related variables, such as electricity prices and inflation are assumed to be objective and forecasting them is based on historical data. Specific investment project related variables, to a great extent, depend on the perception of individual project managers. Indeed, the overall capital costs of a project are partly determined by available subcontractors, and electricity production performance of a future RE power plant depends on available locations. Therefore, the aim of this research is not to make absolutely precise forecasts of investment profitability, but rather to provide a holistic view on the possible realizations of a RE investment, which can then be used by decision-makers as support in investment decision-making and in the development of specific projects.

Other classifications of uncertainty can be found in (Collan et al., 2016), where the authors specifically discuss different types of uncertainty in the context of RO valuation. With respect to the insufficiency of the available information for decision-making, parametric and structural uncertainty can be distinguished. Parametric uncertainty is represented by the situation, where the structure of the problem is known, but the realization of the parameters associated with it is uncertain. Structural uncertainty entails insufficient knowledge (also) about the structure of the problem, e.g., possible consequences of decisions, or technology-related externalities. Apart from information availability related uncertainty, the procedural uncertainty is recognized that relates to the limitations in competencies of individual decision-makers (ibid.).

This research mostly deals with the parametric uncertainty, when it is assumed that the structure of the decision problem is known. Indeed, since the analysis targets investigation of a particular RE support mechanism, the structure of the decision problem and, consequently, the investment models are largely defined by the rules of this mechanism. To tackle procedural uncertainty, the models built in this research are well documented and the results are carefully interpreted.

5. Models constructed within this research

This section aims to present the methodological side of this research. The structure of the general profitability model that underlines all the (other) models built within this research is described in the following subsection. Following the practices of traditional investment analysis, this model is supplemented with sensitivity analyses to provide insights into the Russian RE mechanism effects on investment profitability.

The next two subsections present the implementation of the DMM method and the new extension to enhance the decision-making support achieved from the simulation-based technique. The last subsection documents the model built with the fuzzy pay-off method. These three models utilize the RO valuation logic and aim to provide a deeper understanding of RE investment profitability under the Russian RE support mechanism.

5.1. General profitability model

The investment model used is realized in a spreadsheet environment, Excel®, and follows a traditional logic of the capital budgeting: estimating cash-flows, discounting them, and arriving at NPV and other profitability indicators. The model is based on a stylized RE investment for all the three technology types supported by the Russian mechanism, wind, solar PV, and small hydropower. A distinct feature of the model is that it includes an implementation of the calculation procedure of the RE remuneration provided by the Russian RE capacity mechanism. The outline of the model is illustrated by Figure 7.

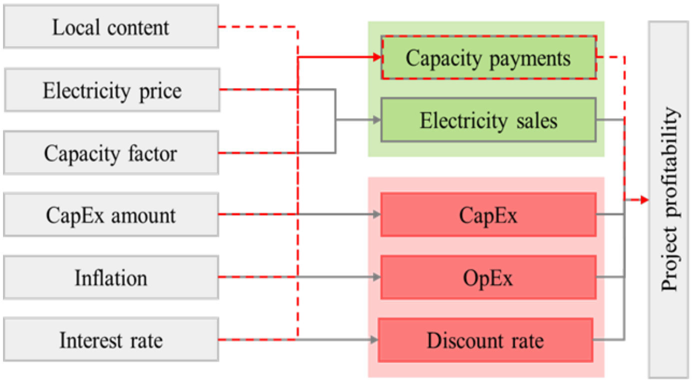

Figure 7. Outline of the RE investment model

Project outflows include capital expenses (CapEx), operational expenses (OpEx), and financial expenses reflected in the discount rate. They are influenced accordingly by the project planned CapEx, inflation, and interest rates. A (generic) project studied has two sources of revenue: i) electricity sales that depend on the market electricity price and electricity production (or capacity factor); ii) revenue from the RE capacity delivery contract. The formation of the capacity price is based on all of the factors listed above, and on the local content of the power plant equipment. A summary of the key variables used and the underlying assumptions are presented in Table 2.

Table 2. List of key input variables

Variable	**Source**	**Assumption**
Electricity price	Average day-ahead market prices in Russia	Forecasted with linear regression, based on historical data, or assumed to be uniformly distributed between extreme values.
Inflation	Russian consumer price index	Forecasted with linear regression, based on historical data, or assumed to be uniformly distributed between extreme values.
Discount rate	WACC calculation based on Russian market data	Assumed fixed. To illustrate the capacity price influence on project profitability under changing market interest, a separate sensitivity analysis of project IRR to local risk-free rate is performed in Publication III.
Capacity factor	Normative levels set by the support mechanism	The base value is set equal to the high level in accordance with the Russian legislation, the variation is checked with sensitivity analysis, or assumed to be uniformly distributed, from 30% to 120% of the base value.
CapEx	Normative CapEx limit	Assumed to be equal to the set limit. Effects of CapEx variation are demonstrated with sensitivity analysis or assumed to have a uniform distribution between 80% and 150% of the base value.
OpEx	Normative value set by the support mechanism	The effects of OpEx variations are checked with sensitivity analysis. Because of low importance, excluded from the list of key variables in later models an assumed to be fixed.
Capacity price	Calculation based on legislative procedure	The inputs to the capacity price calculation are the same as the inputs to the project cash-flow calculation. Russian10-year government bond yield is used as a reference interest rate, in accordance with the legislation.
Local content	The legislative procedure	A binary variable. Assumed to be fulfilled in the base case. In modeling, the case of failing to meet the local content requirement is analyzed.

Sensitivity analysis of the project NPV with regards to seven factors is performed, namely: electricity price, inflation, CapEx, OpEx, capacity factor, discount rate, and the local risk-free rate. All the factors´ values are tested through the range ±50% with a 10% step.

5.2. Monte Carlo simulation model

The Monte Carlo simulation is based on the investment model already described above. The simulation has been implemented in Matlab Simulink® and illustrated with a block-diagram, see Figure 8.

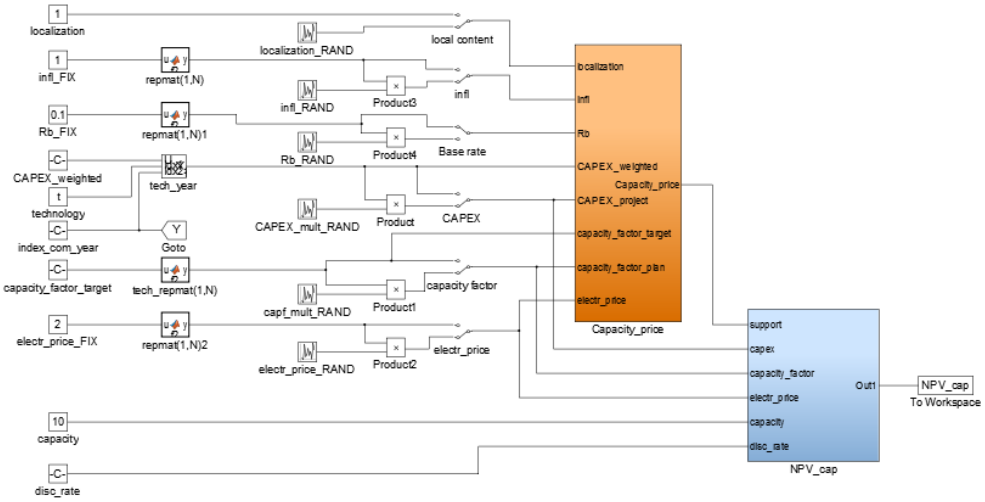

Figure 8. Block diagram of the Monte Carlo simulation model

The blocks on the left of the diagram represent the key input variables. The model also allows running simulations for all three types of RE technologies, defined by the variable ‘technology’. Going from left to right, the inputs are transformed into the format needed for computation, and multiplied by random coefficients that create uniform distributions for the input variables. The orange block contains the capacity price calculation, whereas the blue block computes the project NPV. The resulting NPV vector (result of each simulation run) is “sent” to the Matlab workspace, in which the resulting probability distribution is constructed from the set of results. The Monte Carlo simulation performs 100,000 runs. Different scenarios can be generated by adjusting the random coefficients, and/or by switching inputs to the fixed values.

5.3. The new extension to the simulation model (created new method)

The new decision-support approach for simulation-based methods, created within this research, enables the *decomposition of the created probability distribution* into *a number of sub-distributions*. The sub-distributions consist of (in this case NPV) results created with set (user determined) combinations of variable value sub-ranges. This way the sub-distributions “tell the story” of where one will end up if one is able to “lock-in” on a sub-range of an uncertain variable (to reduce uncertainty) and does not have to face the whole uncertainty (whole range of possible outcomes).

For the purpose of this research, and to create sensible and in reality important sub-ranges, selected key variables (project-internal factors) were identified: local content, capital costs, and capacity factor. In this context the sub-ranges of the identified variables are (quite naturally) given by the Russian RE support mechanism features. The local content requirement is either “fulfilled” or “not fulfilled” and capital costs are divided into two subsets: “within the limit” and “over the limit”. Range of the capacity factor is divided into three subsets, associated with production levels, “high”, “medium”, and “low”, and are set by the support mechanism.

The creation of the sub-distributions is done during the (normal) Monte Carlo simulation, by having MATLAB record, not only the NPV result from the simulation, but also the key variable combination that was randomly drawn and that resulted in the NPV outcome. This is put into practice by introduction of a scenario recording block that works by using the ‘if-then’ principle. In this context, twelve possible sub-range combinations of the key (uncertain) variables are used. The new scenario recording block and its links with the rest of the model are highlighted on Figure 9.

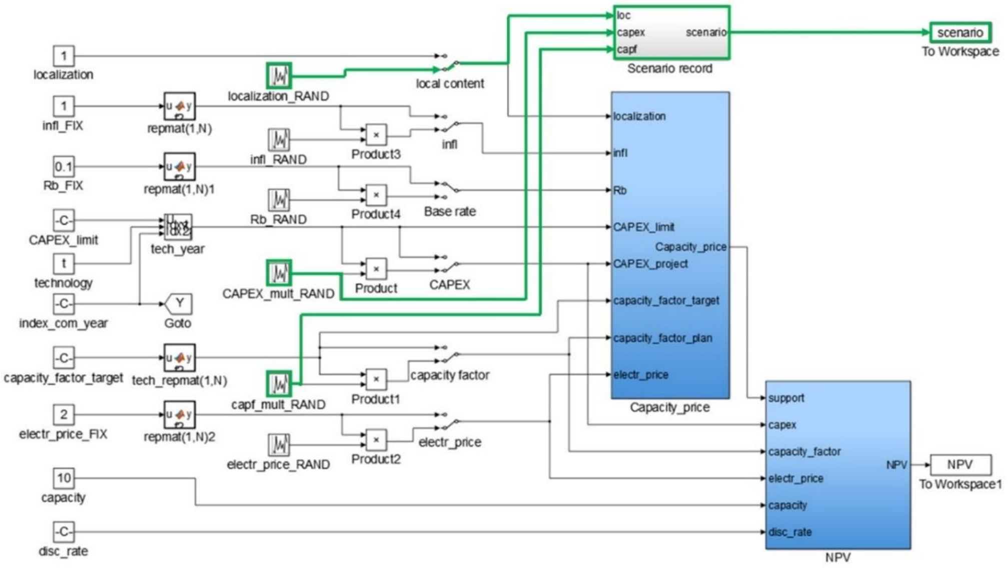

Figure 9. Block diagram of the extended Monte Carlo simulation model. The scenario recording block and links to and from it are highlighted.

The Matlab function, responsible for the creation of the probability distribution of the NPV, is adjusted in a way that it color-codes the created distribution, according to the scenario (variable sub-range combination) underlying each NPV result of the distribution. The resulting distribution allows matching NPV outcomes to key variable states. This enables the user to extract more relevant information for decision-making from the “same simulation”. In addition, separate distributions that correspond to each scenario (sub-range combination) and their descriptive statistics, including RO value, can be obtained, and studied further.

5.4. Pay-off method implementation

The pay-off method is realized with Excel® on top of the created spreadsheet investment model. The triangular pay-off distribution is built, based on three scenarios, where minimum possible (pessimistic) and maximum possible (optimistic) scenarios take the extreme values of the uncertain input variables (defined in Table 2) and the realistic (best guess) scenario takes the base case values.

The pay-off method application is repeated for several cases. In the Russian RE mechanism context, the overall pay-off distribution is first divided into three triangular fuzzy NPVs that reflect three different levels of electricity production performance (“high”, “medium”, and “low”) set by the legislation, with all other factors unchanged and equally uncertain. In the following iteration the capital expenses are assumed to be “within the limit”, and the localization requirement is expected to be fulfilled **-** this is repeated for all three levels of electricity production. In total, seven cases of uncertain factor combinations are illustrated with pay-off distributions, in order to make sensible conclusions, with respect to the support mechanism effects on investment profitability (presented in Publication IV).

6. Publications and summary of results

This section presents an overview of the objectives, methodology, and the main results of the publications that comprise the second part of the thesis. After presenting each publication one by one, the section ends with a concise tabulated summary of the publications.

Publication I is a first inquiry into the Russian RE support mechanism; it presents the remuneration calculation procedure in detail, and demonstrates its effects on RE investment profitability with a simple capital budgeting model and sensitivity analysis. Publication II is a literature review, embracing research that applies the RO valuation approach in RE studies; it provides a solid background for incorporating RO models into the analysis of the Russian RE support mechanism. In Publication III, with the simulation-based model, the effect of the Russian RE support mechanism, on RE investment profitability and on the associated uncertainty, is studied. Publication IV, concentrating on the use of the fuzzy pay-off method, shows how different implementation conditions of RE projects under the Russian mechanism shape the profitability of these investments. The performance and the information content of the simulation-based and the fuzzy set theory-based RO approaches are analyzed and compared in Publication V. Enhanced RO method for the simulation-based model is proposed and introduced in Publication VI, the idea is to better capture the complexity of investment projects and to enhance the support given to decision-making.

6.1. Publication I. Modeling the effects of the new Russian capacity mechanism

Objectives

The first objective of Publication I is to introduce the Russian RE support mechanism, enacted in 2013, and its remuneration calculation procedure in detail. The mechanism has not been previously presented exhaustively in scientific nor in business literature, except for some qualitative analyses and generic discussions. The second objective of Publication I is to conduct a generic profitability analysis of investments receiving remuneration from the Russian RE support mechanism. Furthermore, the effects of the capacity mechanism on the economic viability of investments are explored by way of sensitivity analysis and by comparison with a generic feed-in premium scheme. Finally, Publication I discusses the first actual results (real world outcomes) from the Russian support mechanism implementation in terms of RE type and capacity.

Methodology

Calculation of the capacity price of the Russian support scheme is integrated into a classical capital budgeting model built by means of Excel®. Further, sensitivity of the NPV to a number of input variables is analyzed. The project internal input values are chosen in accordance with the in the support mechanism set targets and limits, whereas project external input values reflect current local market conditions.

Main findings and contribution

To the best of our knowledge, for the first time the procedure of the remuneration calculation of the Russian RE support mechanism is presented exhaustively in English. With this publication, any foreign investor is now able to calculate the amount of support a planned RE project is entitled to.

The conducted sensitivity analysis reveals the benefits of the mechanism to RE investors and accentuates the critical factors that need to be managed. The capacity mechanism shields the profitability of RE projects from volatility in the market factors, such as volatility in electricity prices, the inflation, interest rates, and the exchange rates. The mechanism also encourages investors to plan and maintain a high electricity production performance, and penalizes for higher than the set limits capital costs, and incompletely fulfilled localization requirements. These findings are of use to investors and project planners.

The comparison with a generic feed-in premium scheme highlights the details of the Russian mechanism. In contrast to simply assigning remuneration based on the electricity output from RE projects, the Russian capacity mechanism compensates investors for capacity installed and introduces a flexible remuneration scheme that is able to adapt to a changing market environment and to the specifics of each project. The analysis of the first auctioning (RE project selection) results in Russia, illustrates the successful and the failed features of the mechanism. This unique design of the RE support mechanism can potentially bring new insights to policymakers, planning new support schemes for RE, or upgrading the existing ones.

6.2. Publication II. Real option valuation in renewable energy literature: research focus, trends, and design

Objectives

Publication II is a review of scientific literature that studies RE investments with the RO approach. Separate attention is drawn to papers analyzing various RE support mechanisms. The foci of the review include research design, methodology employed, real options identified, and the state-of-the-art in the field, such as backing up modeling results with real-world evidence, and real options in project, or in policy design.

Methodology

The reviewed material consists of 101 peer-reviewed research papers and 4 existing academic reviews in the field, from the period 2002 – 2017. Sample collection has been conducted via the SCOPUS database.

Main findings and contribution

This paper shows a strong growing trend of research publications that employ RO methodology to analyze RE investments. This is evidence of a growing interest in the academia towards this field. Modest geographical coverage of the case studies shows open possibilities for further research. Most attention in the literature reviewed, is drawn to investment project appraisal. However, there seems to be a rising interest towards RE support mechanism assessment that generally follows actual enactment of supporting schemes in different countries. RO analysis allows assessing the efficiency of a RE promoting scheme, to optimize its design, or to compare it with other policies. With respect to methodology analysis, Publication II summarizes how different research domains and objectives tend to embed different study designs, including methods used, real option types identified, and uncertainty sources accounted for.

The conducted review highlights that researchers, focused on RE power generation valuation, struggle to enable operational flexibility in these projects. A few state-of-the-art works recommend embedding real options into the project design, e.g., backing intermittent RE generation with hydro storage, batteries, or demand-response programs. Another cutting-edge research direction is analyzing and/or designing new, at this time rare, RE support mechanisms that enable operational flexibility to RE power generation investments. Derived conclusions can bring insights, not only to researchers, but also for project planners and policymakers in the field.

6.3. Publication III. Russian Mechanism to Support Renewable Energy Investments: Before and After Analysis

Objectives

Publication III studies the RE investment profitability landscape in Russia with an introduction of the RE support mechanism. In particular, we investigate how surrounding uncertainty shapes investment profitability of RE projects, before and after the introduction of the support mechanism.

Methodology

A system dynamic model of RE investment is built with Matlab Simulink®, and Monte Carlo simulation is run for several scenarios. The input values are chosen so that they cover all aspects of the mechanism targets and limits, as well as reflect current local market conditions.

Main findings and contribution

The simulation results show that without the support mechanism the NPV distribution of a generic wind farm project lies entirely in the negative side that is the investment is always unprofitable, with a maximum value far below -500 million rubles. The support mechanism introduction, together with fulfillment of its requirements by the project, moves the NPV distribution to the positive side and shrinks it (the distribution width is remarkably reduced) making also the minimum value of the distribution to be above zero. This result suggests that the introduction of the support mechanism considerably reduces the uncertainty surrounding RE investments into wind farm projects in Russia, and allows projects to be profitable regardless of changing market environment. This is conditional to the mechanism requirements having been met by the projects. This analysis provides additional insight into the Russian RE support mechanism and its effects on RE investments.

6.4. Publication IV. Renewable Energy in Emerging Economies: Shortly Analyzing the Russian Incentive Mechanisms for Renewable Energy Investments

Objectives

The aim of Publication IV is to analyze Russian RE support mechanisms for both the wholesale and the retail markets in the emerging economies context.

Methodology

A case study of a generic wind farm investment is modeled by the fuzzy pay-off method. The valuation is performed for seven scenarios of a project, with combinations of different levels of compliance with the policy requirements for selected variables.

Main findings and contribution

The paper demonstrates that an emerging economy can choose to design its own support mechanism based on the existing national energy system, instead of adapting to one of the RE support mechanism designs already implemented in the developed countries. The advantages and drawbacks of designing a "new" system are discussed. The numerical example is used to highlight the effects of the Russian support mechanism requirements on the profitability of RE investments under the mechanism that guide the project planners and investors.

6.5. Publication V. Comparison of the Datar-Mathews Method and the Fuzzy Pay-Off Method through Numerical Results

Objectives

Publication V presents a comparative analysis of the performance of two real option valuation methods; Monte Carlo simulation-based Datar-Mathews method and fuzzy set theory-based fuzzy pay-off method for real option valuation.

Methodology

The two methods are used to analyze the same investment case. The results, such as shape of the NPV distribution created, the mean of the created distribution, RO value obtained, and the standard deviation are compared.

Main findings and contribution

The numerical analysis shows that the two methods can be said to provide consistent results. The fuzzy pay-off method for real option valuation is more robust, whereas the shape of the probabilistic distribution resulting from Monte Carlo simulation reveals more details about the uncertainty in the project value. Both methods can be said to fail in representing the complexity of investment projects with interdependent variables. The paper confirms previous results obtained by others.

6.6. Publication VI. Simulation decomposition: new approach for better simulation analysis of multi-variable investment projects

Objectives

The aim of Publication VI is to enhance the simulation-based method for complex investment cases and to demonstrate, with a numerical case, the added value of the technique for decision-making.

Methodology

Taking as a basis the existing model in Matlab Simulink® presented in Publication III, a new module is designed that conducts a decomposition of the performed Monte Carlo simulation. The use of the new approach is demonstrated with a generic investment case in solar PV power plant falling under the Russian RE support mechanism. The decomposition involves breaking the ranges of three uncertain variables into several sub-ranges and deriving twelve separate scenarios from the possible combinations of these subsets. Corresponding to each scenario, sections of the resulting probability distribution, emanating from each respective scenario, are marked with different colors. Descriptive statistics are obtained for each scenario.

Main findings and contribution

This kind of simulation decomposition technique has, to the best of our knowledge, never been presented previously. The only similar methodology we have found was applied in a technical paper to highlight performance levels of engineering devices (García-Redondo, López-Vallejo, Ituero, & Barrio, 2012). It is also known that some consulting companies offer their industrial customers simulation software that is capable of decomposing the result distribution into different scenarios. There does not seem to be any academic / public domain record of such a system available. The paper presents both an algorithm for implementing the method and highlights the obtained benefits for decision-making.

The new method is shown to be beneficial for analyzing complex investment cases, with multiple uncertain variables. A color-coded result distribution allows intuitive matching of outcomes to different scenarios with one glance.

It is also shown that if actively manageable variables are chosen as a basis for the decomposition, the generated results can be used to provide a roadmap of actions for investors that helps them shape the profitability of an investment project. The simulation decomposition approach can easily be integrated into any Monte Carlo simulation model, and can also be used outside of the investment analysis domain, independent of the context. Potential application areas include, but are not limited to, finance and business; social sciences; climate change studies; biology; computational and statistical physics; and various engineering fields, such as microelectronics, robotics, fluid dynamics, and process design.

6.7. Summary of Publications I-VI

Objectives, the methodology used, and the main results of each publication are summarized in Table 3.

Table 3. Summary of the publications

Publication #	Publication I	Publication II	Publication III	Publication IV	Publication V	Publication VI
Title	Modeling the effects of the new Russian capacity mechanism on renewable energy investments	Real option valuation in renewable energy literature: research focus, trends, and design	Russian Mechanism to Support Renewable Energy Investments: Before and After Analysis	Renewable Energy in Emerging Economies: Shortly Analyzing the Russian Incentive Mechanisms for Renewable Energy Investments	Comparison of the Datar-Mathews Method and the Fuzzy Pay-Off Method through Numerical Results	Simulation decomposition: new approach for better simulation analysis of multi-variable investment projects
Objective	To analyze the effects of the new Russian RE support mechanism on RE investments	To review the existing literature that applies RO approach to RE investments	To investigate the shift in RE investment profitability landscape brought by the introduction of the new RE support mechanism in Russia	To inspect Russian RE support mechanisms for both, wholesale and retail markets, in the emerging economies context	To compare results and performance of two, similar in logic, but different in theoretical foundations, RO valuation methods	To enhance the information conveyed by the results of Monte Carlo simulation based investment analyses
Methodology	Classical capital budgeting model in Excel® and sensitivity analysis	Literature review	System dynamic model in Matlab Simulink® and Monte Carlo simulation	Fuzzy set theory based pay-off method model realized in Excel®	Datar-Mathews method with Monte Carlo simulation and the fuzzy pay-off method	Decomposition module on top of simulation based model
Main results	The Russian RE mechanism procedure is presented in detail. The effects to the RE investment profitability are presented in comparison with a generic feed-in premium scheme. Actual mechanism implementation results are gathered and discussed.	Overview of the range of methods and RO types is made and linked to different RE investment problems. Cutting edge research directions are identified.	The effects of the support introduction on RE profitability landscape are presented and discussed. Substantial risk reduction and possibility to lock RE project profitability in the positive zone under the new scheme are demonstrated.	Advantages and drawbacks of designing a RE support mechanism based on local energy market rules in emerging economy are discussed. The effects of the Russian mechanism requirements on RE investments are highlighted.	The performance and results of the two methods are compared. Conclusions about their suitability to investment problems are derived and discussed.	Simulation-based approach to investment analysis is enhanced with a new decomposition technique that links scenarios to associated outcomes. The applicability and added value of the new method is demonstrated with a numerical example.

7. Discussion and conclusions

Focusing on the Russian RE support mechanism, this research aims to analyze its effects on RE investments, as well as, to enhance existing RO methods to better support decision making. Two specific research questions have been formulated. Answers to these research questions, contribution, and implications of this research are elaborated in this section. Limitations of this research and future research directions are discussed.

7.1. Answering the research questions

The two set research questions are answered by providing answers to the sub-questions, to which they are divided into. The first research question concerns the design of the Russian RE support mechanism, and its effects on RE investment profitability.

RQ #1.1. What is the detailed design of the Russian RE support mechanism and what is the procedure used in the remuneration calculation?

This research question is answered in Publication I. It outlines the mechanism design and its origins, reveals its crucial requirements for participating RE projects, and presents the detailed procedure of the capacity price calculation. It is shown that the Russian RE support mechanism represents a unique scheme that is to a great extent different from the existing other schemes to support RE. Particularly it provides support, not for the electricity produced (in terms of MWh), but for capacity installed (in terms of MW). This approach originates from the pre-existing capacity market rules in the Russian energy system and is, in fact, an extension to these rules that is adapted for RE investments. The remuneration calculation is designed in a way that it guarantees a certain (riskless) return on investment, shielding investments from a volatile market environment. Capacity price is adjusted throughout the lifetime of a project, based on changes in electricity prices, inflation, and interest rates. To be able to benefit from these safeguards, RE projects have to comply with the mechanism requirements that include a capital cost limit, production targets, and a local content requirement.

RQ #1.2. What are the key drivers of profitability for Russian RE investments under the new RE support mechanism?

In publication I it is demonstrated that the additional capacity revenue from the RE support mechanism makes RE investments not only profitable, but also diminishes their dependence on the changing electricity prices and on inflation. The profitability of RE projects will suffer from non-compliance with the mechanism requirements regarding capital costs, localization, and electricity production performance. These effects are further elaborated in Publication III with the simulation based model. This analysis reveals that profitability of RE investments can be locked in to the positive zone (positive profitability) under the Russian RE support mechanism, by making sure that the project meets the aforementioned requirements. Similar guarantee is not presently provided by any other type of RE support design.

Publication IV provides profitability distributions of a RE project under the Russian mechanism for different scenarios, when a project meets policy requirements. Finally, the new simulation decomposition framework has been used in Paper VI to show under which circumstances (scenarios composed of variable range combinations) investment cases are profitable under the Russian RE mechanism.

RQ #1.3. What insights do RO valuation techniques bring to the Russian RE support mechanism analysis?

The literature review presented in Publication II presents the variety of RO approaches used in analysis of RE investments, and underlines the general conclusion that RO analysis is a more advanced technique of profitability analysis, than the typically used classical capital budgeting methods are. With respect to the analysis of the Russian RE support mechanism effects on RE investments, it can be said that both used real option valuation methods (simulation-based and fuzzy set theory-based) have brought additional insight. Publications III and IV show that both methods are able to capture the type of uncertainty surrounding investments in the Russian RE context, and demonstrate how the RE support mechanism is able to reduce that uncertainty. If a RE investment into the Russian markets is thought as an option, it can be said that the analyses performed show how close the option is to be in the money and what the effect of the Russian RE support mechanism is on the option value. The conclusions derived from the analyses of these publications indicate that there is reason to believe that RO valuation brings substantial added value over classical capital budgeting methods in the context of this thesis.

Publication II draws, based on previous research, the conclusion that the choice of the method used should reflects the type of uncertainty present and the case analyzed. In the Russian RE investment context the type of uncertainty is parametric, and therefore methods that are able to handle this type of uncertainty have been chosen. The chosen methods, the Datar-Mathews Method and the Fuzzy Pay-Off Method for Real Option Valuation seem to be quite suitable for the analyses, however, they are different and the simulation-based DMM method seems to be able to provide more fine-grained results.

Investment timing and capacity choice issues, that can be studied within the real options analysis framework, have not been studied in this research. Optimizing timing and capacity is left as an issue for further research.

The second research question targets improvement of existing RO approaches.

RQ #2.1. What shortcomings of the Datar-Mathews method and the fuzzy pay-off method for real option valuation can be identified?

The performance and the results from using the two selected RO models are compared in Publication V. Both methods are found to work rather well and to give overall general information about the profitability of investments (in the Russian RE context). However, when detailed information about the connection between uncertain variables and the end result (profitability) is analyzed these methods are not able to deliver good answers. This limitation can be “eased” by performing additional analyses, such as sensitivity analysis – this has been done in Publications III and IV.

RQ #2.2. How could the identified shortcomings of these methods be resolved?

As the identified shortcoming has to do with establishing the connection between variable states and groups of variable states and the resulting NPV, a “cure” would be something that allows decision-makers to gain better understanding of this connection. Furthermore, it is clear that if new additions are made to old methods it is “nice” that the end result is (if only possible) as easy to use as the original non-enhanced method. In this case it means that a remedy must allow simultaneous capturing of the said connection and calculation of the end result.

In this research a new enhancement to the Monte Carlo simulation-based profitability analysis methods was created and put into a usable algorithm form. The idea of the new simulation decomposition method that allows (even visual) decision support to investment decision-making, with regards to the connection of variable values and the end result, is presented in Publication VI. In practical use, the value ranges of the uncertain input variables are matched with the resulting outcomes (ranges) by color-coding (visible in the resulting probability distribution). This way the benefits of the sensitivity, scenario, and simulation analyses can be combined into one intuitive graphical presentation. The new approach is computationally light, easy to implement, and the results are intuitively understandable. In a Matlab environment (used in this research) it is possible to enable and to automate the use of the new method without any additional steps for the user. The new method offers greater information content for decision-making, and is especially useful for analyzing the Russian RE support mechanism, with step-wise causalities of set requirements.

The idea behind simulation decomposition can be realized also for the fuzzy set theory-based pay-off method by combining the pay-off method with a fuzzy inference system construct. This approach has, however, been left for further study and remains outside the scope of this research at this time.

7.2. Contributions of this research

Firstly, this research contributes to the RE policy studies by offering an introduction and an analysis of the Russian RE support mechanism in a previously unseen detail. To the best of our knowledge, the mechanism’s remuneration calculation procedure has been entirely presented here for the first time in English. This research is also the first to numerically analyze the effects of the Russian RE support mechanism on RE investment profitability.

Secondly, the literature review conducted within this research includes more than 100 scientific papers and outlines trends and research design in the study of RE investments with the RO approach. State-of-the-art research directions are revealed and guide researchers in focusing their future work.

Thirdly, the new simulation decomposition method enhances the understandability of multi-variable Monte Carlo simulation results and offers remarkable added value for decision making. The method is presented in a form of a usable algorithm and its use illustrated with a numerical example. Although the method has been created in the context of studying the Russian RE support mechanism, its application is not limited to this context, but can be extended to investment profitability analysis in general and to fields of science beyond business research.

7.3. Implications for researchers, project managers, and policymakers

This research creates important new knowledge for different stakeholders in the RE industry about the Russian RE support mechanism. Investors and project managers considering RE power generation investments in Russia, within the wholesale market, where the capacity mechanism is in force, should be aware of its details and how the mechanism works. The crucial issue to consider when investments are planned is being able to comply with the policy requirements, meeting the local content requirement, keeping the capital costs within set limits, and planning the location of a power plant, where it can reach high levels of electricity production. With the requirements met, the project profitability can be expected to be in a much “better shape”, due to the RE mechanism offering a shield against the changes in the market environment. The analysis shows that after a project has been selected for the capacity contract, only a modest capital overspending can be allowed for profitability to remain. Moreover, the planned project realization schedule should be kept, otherwise considerable negative to the profitability “fees” will be applied.

Also English speaking policymakers are now equipped with the possibility to acquaint themselves with another possible design of a RE support mechanism. The mechanism can be considered unique in terms of the remuneration design and terms of the tradeoff between effectiveness of RE promotion and cost. Being highly controllable, the Russian design could be a reasonable solution for emerging economies. The lessons learned from the practical realization of the mechanism in Russia highlight the importance of carefully tuning the requirements to be met by the participants. Too strict requirements / limits may scare off new investments.

7.4. Limitations of the research

Any research is limited by the focus taken and by the methods selected - this applies also to this research.

One important issue to recognize, when scrutinizing this research is that the numerical results have been achieved by using a stylized investment case that may, or may not, be applicable to the planning of real-world RE investments.

The numerical assumptions made are not necessarily (completely) reflecting the unfolding future states of the Russian market, however, this limitation is to some extent neutralized by the sensitivity analysis and the uncertainty embedded into modeling.

The models selected are a subset of all real option analysis methods available. Using a larger selection of models may bring additional insight that has not come out in this research.

The validity of the conclusions made is to some extent supported by the already existing evidence from the first RE investment auctions in Russia, time will tell if the conclusions made hold the test of time.

7.5. Future research directions

With respect to the Russian RE mechanism analysis, this research could be extended to cover the geographical differences within Russia. Such an extension would provide a more detailed roadmap for investors that would consider also the different Russian locations. In fact, alongside the differences in RE sources availability (for example, average wind speeds / solar radiation), different regions in Russia possess various levels of new capacity needs, as well as, hold significant differences in the quality of (electricity transfer) networks and in other electrical infrastructure. These are important factors for planning RE power generation investments and their variations within the country should be considered.

Another novel research direction in this field is to seek and report evidence from managers of actual started RE projects. Such evidence “from the inside” would perhaps shed light on the hidden risks of RE investments in Russia.

In a broader RE policy context, comparison of the Russian mechanism with other existing support schemes, and suggesting new RE support policy designs, perhaps tuned for particular needs of different countries, would benefit policymakers.

Concerning enhancing RO methodology, the simulation decomposition method idea can be extended to the fuzzy case, perhaps by constructing an additional fuzzy inference system to complement the pay-off method “frame”.

References

Allenotor, D. (2011). *A fuzzy real option model for pricing grid compute resources*. University of Manitoba.

Amram, M., & Kulatilaka, N. (1998). *Real options: Managing strategic investment in an uncertain world*. Oxford University Press.

Ashby, W. R. (1991). Requisite variety and its implications for the control of complex systems. *Facets of systems science* (pp. 405-417) Springer.

Balibrea-Iniesta, J., Sánchez-Soliño, A., & Lara-Galera, A. (2015). Application of real options theory to the assessment of public incentives for onshore wind energy development in Spain. *International Journal of Energy Economics and Policy, 5*(3), 791-800.

Bednyagin, D., & Gnansounou, E. (2011). Real options valuation of fusion energy R&D programme. *Energy Policy, 39*(1), 116-130.

Black, F., & Scholes, M. (1973). The pricing of options and corporate liabilities. *The Journal of Political Economy*, 637-654.

Black, M. (1962). *Models and metaphors: Studies in language and philosophy*. Ithaca, NY, US: Cornell Univer. Press.

Block, S. (2007). Are "real options" actually used in the real world? *The Engineering Economist, 52*(3), 255-267.

Boomsma, T. K., & Linnerud, K. (2015). Market and policy risk under different renewable electricity support schemes. *Energy, 89*, 435-448.

Boomsma, T. K., Meade, N., & Fleten, S. (2012). Renewable energy investments under different support schemes: A real options approach. *European Journal of Operational Research, 220*(1), 225-237.

Boute, A. (2015). *Russian electricity and energy investment law*. Boston, BRILL.

Boute, A. (2012). Promoting renewable energy through capacity markets: An analysis of the Russian support scheme. *Energy Policy, 46*(0), 68-77.

Carlsson, C., & Fullér, R. (2011). *Possibility for decision: A possibilistic approach to real life decisions*. Springer Science & Business Media.

Collan, M. (2011). Valuation of industrial giga-investments: Theory and practice. *Fuzzy Economic Review, 16*(1), 21.

Collan, M., & Heikkilä, M. (2011). Enhancing patent valuation with the pay-off method. *Journal of Intellectual Property Rights, 16*(5), 377-384.

Collan, M., Fullér, R., & Mezei, J. (2009). A fuzzy pay-off method for real option valuation. *Journal of Applied Mathematics and Decision Sciences, 2009*, 1-14.

Collan, M., Haahtela, T., & Kyläheiko, K. (2016). On the usability of real option valuation model types under different types of uncertainty. *International Journal of Business Innovation and Research*, (11(1)), 18-37.

Cox, J. C., Ross, S. A., & Rubinstein, M. (1979). Option pricing: A simplified approach. *Journal of Financial Economics, 7*(3), 229-263.

Datar, V. T., & Mathews, S. H. (2004). European real options: An intuitive algorithm for the Black-Scholes formula. *Journal of Applied Finance, 14*(1), 45-51.

Eryilmaz, D., & Homans, F. R. (2016). How does uncertainty in renewable energy policy affect decisions to invest in wind energy? *The Electricity Journal, 29*(3), 64-71.

Fernandes, B., Cunha, J., & Ferreira, P. (2011). The use of real options approach in energy sector investments. *Renewable and Sustainable Energy Reviews, 15*(9), 4491-4497.

Fisher, I. (1907). *The rate of interest: Its nature, determination and relation to economic phenomena*. Macmillan.

Frankfurt School UNEP Collaborating Centre & Bloomberg New Energy Finance. (2016). *Global trends in renewable energy investment 2016.* Retrieved from http://fs-unep-centre.org/publications/global-trends-renewable-energy-investment-2016

Fuss, S., Johansson, D. J. A., Szolgayova, J., & Obersteiner, M. (2009). Impact of climate policy uncertainty on the adoption of electricity generating technologies. *Energy Policy, 37*(2), 733-743.

García-Redondo, F., López-Vallejo, M., Ituero, P., & Barrio, C. L. (2012). A CAD framework for the characterization and use of memristor models. *Synthesis, Modeling, Analysis and Simulation Methods and Applications to Circuit Design (SMACD), 2012 International Conference On,* 25-28.

Government of Russian Federation, 28 may 2013 decree #449 on the mechanism of promoting the use of renewable energy in the wholesale market of electric energy and power, (2013a).

Government of Russian Federation, 28 may 2013 resolution #861-r on amendments being made to resolution #1-r 8.01.2009 on the main directions for the state policy to improve the energy efficiency of the electricity sector on the basis of renewable energy sources for the period up to 2020, (2013b).

Graham, J. R., & Harvey, C. R. (2001). The theory and practice of corporate finance: Evidence from the field. *Journal of Financial Economics, 60*(2–3), 187-243.

Gray, A. A., Arabshahi, P., Lamassoure, E., Okino, C., & Andringa, J. (2005). A real options framework for space mission design. *2005 IEEE Aerospace Conference,* 137-146.

Hassanzadeh, F., Collan, M., & Modarres, M. (2012). A practical approach to R&D portfolio selection using the fuzzy pay-off method. *Fuzzy Systems, IEEE Transactions On, 20*(4), 615-622.

Held, C., & Voss, J. O. (2013). Legal limits for electricity capacity markets in the EU and Germany. *Renewable Energy Law and Policy Review, 4*, 245-253.

Hobbs, B. F., Hu, M., Iñón, J. G., Stoft, S. E., & Bhavaraju, M. P. (2007). A dynamic analysis of a demand curve-based capacity market proposal: The PJM reliability pricing model. *Power Systems, IEEE Transactions On, 22*(1), 3-14.

Iniesta, J. B., & Barroso, M. M. (2015). Assessment of offshore wind energy projects in Denmark. A comparative study with onshore projects based on regulatory real options. *Journal of Solar Energy Engineering, Transactions of the ASME, 137*(4)

International Finance Corporation. (2013). Russia's new capacity-based renewable energy support scheme. an analysis of decree no. 449. Retrieved from http://www.ifc.org/wps/wcm/connect/f818b00042a762138b17af0dc33b630b/Energy-Suppor-Scheme-Eng.pdf?MOD=AJPERES

Jeon, C., Lee, J., & Shin, J. (2015). Optimal subsidy estimation method using system dynamics and the real option model: Photovoltaic technology case. *Applied Energy, 142*, 33-43.

Johnson, S., Taylor, T., & Ford, D. (2006). Using system dynamics to extend real options use: Insights from the oil & gas industry. *International System Dynamics Conference,* 23-27.

Kim, B., Lim, H., Kim, H., & Hong, T. (2012). Determining the value of governmental subsidies for the installation of clean energy systems using real options. *Journal of Construction Engineering and Management, 138*(3), 422-430.

Kim, K., & Lee, C. (2012). Evaluation and optimization of feed-in tariffs. *Energy Policy, 49*(0), 192-203.

Kitzing, L., Juul, N., Drud, M., & Boomsma, T. K. (2017). A real options approach to analyse wind energy investments under different support schemes. *Applied Energy, 188*, 83-96.

Kozlova, M., Collan, M., & Luukka, P. (2015). Renewable energy in emerging economies: Shortly analyzing the Russian incentive mechanisms for renewable energy investments. *International Research Conference "GSOM Emerging Markets Conference-2015: Business and Government Perspectives",* Saint-Petersburg, Russia.

Kumbaroğlu, G., Madlener, R., & Demirel, M. (2008). A real options evaluation model for the diffusion prospects of new renewable power generation technologies. *Energy Economics, 30*(4), 1882-1908.

Lall, P., Lowe, R., Goebel, K., & Cooper, W. (2012). Cost assessment for implementation of embedded prognostic health management for electronic systems. *Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm), 2012 13th IEEE Intersociety Conference On,* 487-497.

Lawson, T. (1988). Probability and uncertainty in economic analysis. *Journal of Post Keynesian Economics, 11*(1), 38-65.

Lee, S., & Shih, L. (2011). Enhancing renewable and sustainable energy development based on an options-based policy evaluation framework: Case study of wind energy technology in Taiwan. *Renewable and Sustainable Energy Reviews, 15*(5), 2185-2198.

Lin, B., & Wesseh Jr, P. K. (2013). Valuing Chinese feed-in tariffs program for solar power generation: A real options analysis. *Renewable and Sustainable Energy Reviews, 28*(0), 474-482.

MacDougall, S. L. (2015). The value of delay in tidal energy development. *Energy Policy, 87*, 438-446.

Martínez Ceseña, E. A., Mutale, J., & Rivas-Dávalos, F. (2013). Real options theory applied to electricity generation projects: A review. *Renewable and Sustainable Energy Reviews, 19*(0), 573-581.

Marx, K. (1894). In Engels F. (Ed.), *Capital: A critique of political economy, vol. III. the process of capitalist production as a whole* [Das Kapital, Kritik der politischen Ökonomie] (E. Untermann Trans.). Chicago: Charles H. Kerr and Co.

Mathews, S. (2009). Valuing risky projects with real options. *Research-Technology Management, 52*(5), 32-41.

Mathews, S., & Salmon, J. (2007). Business engineering: A practical approach to valuing high-risk, highreturn projects using real options. *Tutorials in Operations Research, Chapter 9*, 157-175.

Mathews, S., Datar, V., & Johnson, B. (2007). A practical method for valuing real options: The Boeing approach. *Journal of Applied Corporate Finance, 19*(2), 95-104.

Menegaki, A. (2008). Valuation for renewable energy: A comparative review. *Renewable and Sustainable Energy Reviews, 12*(9), 2422-2437.

Mitroff, I. I., Betz, F., Pondy, L. R., & Sagasti, F. (1974). On managing science in the systems age: Two schemas for the study of science as a whole systems phenomenon. *Interfaces, 4*(3), 46-58.

Monjas-Barroso, M., & Balibrea-Iniesta, J. (2013). Valuation of projects for power generation with renewable energy: A comparative study based on real regulatory options. *Energy Policy, 55*(0), 335-352.

O'Regan, B., & Moles, R. (2001). A system dynamics model of mining industry investment decisions within the context of environmental policy. *Journal of Environmental Planning and Management, 44*(2), 245-262.

REN21. (2016). Renewables 2016 global status report. Retrieved from http://www.ren21.net/wp-content/uploads/2016/10/REN21_GSR2016_FullReport_en_11.pdf

Ritzenhofen, I., & Spinler, S. (2016). Optimal design of feed-in-tariffs to stimulate renewable energy investments under regulatory uncertainty - A real options analysis. *Energy Economics, 53*, 76-89.

Ryan, P. A., & Ryan, G. P. (2002). Capital budgeting practices of the fortune 1000: How have things changed. *Journal of Business and Management, 8*(4), 355-364.

Scatasta, S., & Mennel, T. (2009). Comparing feed-in-tariffs and renewable obligation certificates-the case of wind farming. *Annual International Conference on Real Options.*

Sheen, J. (2014). Real option analysis for renewable energy investment under uncertainty. *Proceedings of the 2nd International Conference on Intelligent Technologies and Engineering Systems (ICITES2013)*, 283-289.

Smeets, N. (2017). Similar goals, divergent motives. the enabling and constraining factors of russia's capacity-based renewable energy support scheme. *Energy Policy, 101*, 138-149.

Sontamino, P., & Drebenstedt, C. (2014). A prototype decision making tool of coal mine planning using system dynamics model. *Mine planning and equipment selection* (pp. 1475-1484) Springer.

Swoyer, C. (1991). Structural representation and surrogative reasoning. *Synthese, 87*(3), 449-508.

Tan, B., Anderson, E. G., Dyer, J. S., & Parker, G. G. (2010). Evaluating system dynamics models of risky projects using decision trees: Alternative energy projects as an illustrative example. *System Dynamics Review, 26*(1), 1-17.

Teller, P. (2001). Twilight of the perfect model model. *Erkenntnis, 55*(3), 393-415.

Tennbakk, B., Lafitte, J., Capros, P., Delkis, C., Tasios, N., Zabara, M., Jenssen, Å. (2013). Capacity mechanisms in individual markets within the IEM. Retrieved from https://ec.europa.eu/energy/sites/ener/files/documents/20130207_generation_adequacy_study.pdf

Trigeorgis, L. (1995). *Real options: An overview*. Praeger Westport, CT.

Trigeorgis, L. (1996). *Real options: Managerial flexibility and strategy in resource allocation*. MIT press.

Vasileva, E., Viljainen, S., Sulamaa, P., & Kuleshov, D. (2015). RES support in Russia: Impact on capacity and electricity market prices. *Renewable Energy, 76*(0), 82-90.

Wesseh, P. K., & Lin, B. (2016). A real options valuation of Chinese wind energy technologies for power generation: Do benefits from the feed-in tariffs outweigh costs? *Journal of Cleaner Production, 112*, 1591-1599.

Yu, W., Sheblé, G. B., Lopes, J. A. P., & Matos, M. A. (2006). Valuation of switchable tariff for wind energy. *Electric Power Systems Research, 76*(5), 382-388.

Zhang, M., Zhou, D., Zhou, P., & Liu, G. (2016). Optimal feed-in tariff for solar photovoltaic power generation in China: A real options analysis. *Energy Policy, 97*, 181-192.

Zhang, M., Zhou, D., & Zhou, P. (2014). A real option model for renewable energy policy evaluation with application to solar PV power generation in China. *Renewable and Sustainable Energy Reviews, 40*, 944-955.

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Modeling the effects of the new Russian capacity mechanism on renewable energy investments

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Modeling the effects of the new Russian capacity mechanism on renewable energy investments

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HIGHLIGHTS

- New Russian RE investment incentive mechanism is presented in detail.
- Effect of the mechanism on RE investment profitability is numerically illustrated.
- Sensitivity of project profitability to selected variables is studied.
- Sensitivity results are compared to results under a generic feed-in premium.
- The mechanism is shown to reduce market-related risks of RE investments.

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ABSTRACT

Russian renewable energy policy, introduced in May 2013, is a capacity mechanism-based approach to support wind, solar, and small hydro power development in Russia. This paper explores the effect of the new mechanism on the profitability of new renewable energy investments with a numerical example. The sensitivity of project profitability to selected factors is studied and the results are compared ceteris paribus to results from a generic feed-in premium case. Furthermore, the paper gives a complete and detailed presentation of the capacity price calculation procedure tied to the support mechanism.

The results show that the new Russian renewable energy capacity mechanism offers a significant risk reduction to the investor in the form of dampening the sensitivity to external market factors. At the same time it shields the energy market system from excessive burden of renewable energy support. Even if the complexity of the method is a clear drawback to the detailed understanding of how the mechanism works, the design of the incentive policy could be an appealing alternative also for other emerging economies.

1. Introduction

This paper studies the effect that the recently introduced Russian renewable energy (RE) incentive policy for the wholesale electricity market has on new renewable energy project investment profitability. This policy is an extension of the Russian pre-existing capacity trade mechanism and it is considerably different from other renewable energy support schemes implemented worldwide. We present the Russian RE incentive policy in detail, show how it affects RE investment profitability, and analyze the importance of the main variables of the policy mechanism on investment profitability.

The Russian RE investment support policy has been launched based on the background of the threat of global warming and the exhaustion of non-renewable energy resources that have caused the Russian government, in unison with many other governments around the world, to act in favor of RE investments. Renewable energy adoption and its diffusion that is taking place worldwide owes partly to the introduction of RE supporting mechanisms and this is why support mechanism design is a key factor in determining how much new RE power generation investments are started, i. e., the support mechanisms are an important determinant in how well RE supporting policies fair in terms of efficiency (del Río and Cerdá, 2014). It is important to note in this vein that

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Abbreviations: ATS - Administrator of Trading System; CAPEX - Capital expenditures; CIA - Central Intelligence Agency; CPI - Consumer price index; DPM - Agreements for the delivery of capacity; FiT - Feed-in tariffs; NPV - Net present value; OJSC - Open joint-stock company; OPEX - Operational expenditures; RAO UES - Unified Energy System of Russia; RE - Renewable energy; RPS - Renewable portfolio standard; SO - System Operator

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RE policy designs differ from country to country (International Energy Agency and International Renewable Energy Agency, 2014). Most of the RE support schemes used can be grouped into three system design types that are feed-in tariffs (FIT), tender- or auction-based term-based tariff systems, and renewable energy portfolio standards (RPS), or quota systems (REN21, 2015). The feed-in-tariff designs introduce a guaranteed (often fixed) special price, or a price premium, for generated RE electricity and there is evidence to suggest that these have been successful in incentivizing RE deployment (Fais et al., 2014; Lund, 2007; Maurer and Barroso, 2011). There is evidence to suggest that feed-in-tariffs may be a more expensive policy alternative for the "tax payer", than renewable energy portfolio standards, where pricing of generated RE electricity is typically set by the markets (Maurer and Barroso, 2011; Azuela and Barroso, 2012). Auction-based schemes attempt to find a balance between set (fixed) and the market pricing, by creating a market-based price for term contracts that then provide a fixed term price (del Río and Linares, 2014; Maurer and Barroso, 2011).

Developed countries have played a pioneering role in RE deployment, but for the last years, emerging economies show higher growth in new RE investments (Frankfurt School UNEP Collaborating Centre and Bloomberg New Energy Finance, 2015). Indeed, recent studies report empirical evidence of positive causality between RE consumption and economic growth in different parts of the world (Apergis and Payne, 2010; Apergis and Payne, 2011; Salim and Rafiq, 2012). Designing RE support policies in emerging economies seems to be a task that is challenged by many potential obstacles, e. g., including political and regulatory risks, typically higher market sensitivity to shocks, and a limited access to financing (Timilsina et al., 2012; Pegels, 2010; Beck and Martinot, 2004). Furthermore, difficulty to recruit human resources with the needed know-how and poor information and documentation availability may also cause hardship for RE support system design projects in emerging economies (International Finance Corporation, 2011). Under these circumstances, emerging economies have most often resorted to adopting RE support schemes that are already in place elsewhere, by perhaps slightly adapting them for the local circumstances and/or by integrating components from different already-existing schemes to the local pre-existing systems (REN21, 2015).

Feed-in tariffs have been the "system of choice" for the majority of developing countries that have adopted a RE support system and they have spread particularly to Asian and to African countries. Some emerging economies have adopted auction-based RE support schemes, especially countries in Latin and in Central America. Renewable energy portfolio standards that typically allocate more risks to the investors, appear not to have become very popular among the developing countries (International Energy Agency and International Renewable Energy Agency, 2014; REN21, 2015). In response to policy failures and deficiencies in local circumstances, many developing countries have moved from one type of RE supporting mechanism to another, sometimes leaving the first initiated system in force for specific RE segments. Examples of such "policy migration" include, e. g., Brazil's shift from feed-in-tariffs to an auction-based system, China's move from auctions to FIT followed by a focused re-introduction of auctions for particular technology types, and the Indian launch of auctions on top of a pre-existing FIT system and RE certificate markets (Azuela and Barroso, 2012).

Contrary to the strategy of many other developing countries to adopt pre-existing RE policy instruments, Russia has recently introduced a new and unique design for a RE support system that is based on capacity remuneration. The foundation of the new RE capacity mechanism is the pre-existing Russian capacity trade mechanism for conventional electricity production that tries to ensure the sustainability and smooth functioning of the Russian energy system. Adopted now for renewable energy support, the Russian RE support mechanism neither guarantees a particular price, nor allows the price to be fully formed by the markets. Instead the Russian mechanism is a set of specific remuneration calculation procedures that try to ensure a set fixed return on RE investments that is able to adapt to changing market conditions throughout a (support) contract term. The contracts are auctioned. Capacity remuneration approaches have also been implemented elsewhere in the world to enhance the reliability of electricity markets (Tennbakk et al., 2013; Hobbs et al., 2007; Held and Voss, 2013), but never before have they been adopted to support renewable energy investment.

Information available about the Russian renewable energy policy is rather limited on the international arena, because the original legislative procedures and capacity pricing instructions are publicly available only in the Russian language (Government of Russian Federation, 2013a; Government of Russian Federation, 2013b; Government of Russian Federation, 2015). The policy has been previously descriptively analyzed in English by the International Finance Corporation (IFC) (International Finance Corporation, 2013) in a way that is sufficient for obtaining a preliminary perception of the RE support mechanism, but not detailed enough for a full understanding of its effects on renewable energy investment deployment. In the academic literature, Russian renewable energy policy in general has received some attention prior to the introduction of the capacity mechanism, e.g., see (Martinot, 1998; Martinot, 1999; Zhang et al., 2011). In addition, the prospects of renewable energy development on the regional level and in the remote areas of Russia have been previously studied (Boute, 2013, 2016).

Literature that concentrates on the capacity mechanism, which is the main scheme to support RE in Russia and the only scheme available within the wholesale market of electricity is very limited. Anatole Boute of the IFC (Boute, 2012) studies the mechanism based of a legislative act draft available at the time of his writing, the paper is positive about the ability of the Russian (then planned) scheme to create appropriate incentives for new RE investments. The final details and a detailed presentation of the final remuneration calculations are not included for the obvious reasons. Vasileva and others Vasileva et al. (2015) have analyzed the RE capacity mechanism from a different perspective, modeling its possible impact on the electricity and the capacity prices on the Russian energy market, their results suggest only minor influence. Existing business and academic literature in English on the Russian RE support mechanism is fragmentary and does not fully present the remuneration logic of the said mechanism, the effects of the mechanism on RE investment profitability, and any consecutive implications for investors and policymakers have so far not been comprehensively analyzed.

In this vein, and in order to fill the observed research gap with regards to the Russian RE support system, this paper: i) describes the Russian RE support system and puts it in an international context; ii) numerically illustrates and analyzes the effect of how the said system affects the profitability of RE investments in Russia - the results shed new light on how the key policy features of the mechanism affect RE investment profitability, and iii) uncovers insights on policy implications for investors and for the Russian energy market system as a whole.

Furthermore, the paper presents, as an appendix, a detailed description of the Russian capacity pricing mechanism for the wholesale market RE in English – this is to clarify in fine grain the underlying Russian system, and while the presentation is a close reproduction of the relevant Russian laws in English and as such are not a scientific contribution at all, it is to the best of our knowledge among the first such presentations in English.

In the following section, we introduce the Russian electricity market in general and the capacity market in detail. This is followed by a description of the new renewable energy capacity mechanism, of how it is applied, and a presentation of a calculation model that is built for the purpose of analyzing the mechanism. Then a presentation of the results obtained with the model and from a sensitivity analysis performed follows. For the purposes of comparison, the model and the sensitivity analysis results are compared to results obtained from a stylized feed-in tariff mechanism model to highlight the differences between the Russian RE support mechanism and the most widely to the emerging economies spread FIT mechanism. The paper is closed with a discussion and conclusions.

2. Russian wholesale power market and the new capacity mechanism for RE investments

According to the CIA World Factbook Russia is ranked fourth in electricity production after China, the US, and the EU (Central Intelligence Agency, 2014). As of 2012, the total installed electricity generation capacity in Russia was 223 GW. In 2012, more than 1000 TWh of electricity was produced, thereof more than 60% by thermal power stations. Nuclear, and hydropower plants both accounted for approximately 15% of the total power production. Renewable energy sources accounted only for about 1% of the total electricity production (which mostly constitutes of expensive diesel generation substitution in remote areas, with no access to the grid). 98.5% of the produced electricity was consumed in Russia and the rest exported (Russian Ministry of Energy, 2013). Electricity consumption in Russia has been constantly growing at an average rate of 2% per year, since the year 2000 (data from the World Bank World Development Indicators Database), which is roughly the equivalent of 8 GW of new installed capacity each year.

There are two commodities in the Russian electricity markets, electricity and capacity. Electricity is traded through bilateral contracts in a day-ahead market and in an intra-day balancing market. Bilateral contracts allow electricity buyers and producers to negotiate price, quantity, and supply duration directly with each other, and independently of the prevalent market conditions. The day-ahead-market is a wholesale electricity market for trades that are made a day before the actual delivery. The trade is organized in two steps: first, one week before delivery, power generators submit technical information to the power system operator OJSC “System Operator of the Unified Power System” (SO) and it forecasts the consumption and selects enough production units (by the power generators) to cover it. Second, one day before delivery, power generators selected in the first step submit price offers to the trading operator (OJSC) “Trading System Administrator” (ATS) that then selects the best offers, based on the price order (NP Market Council, 2012).

The clearing price that all power generators receive for the electricity is set at the most expensive price of the selected offers. Due to imperfect transmission capacity between some areas, power generator selection and price definition are performed separately. Overall, there are about 8000 nodes (areas) in the Russian power system that are aggregated into two price zones, on the grounds of the prevailing energy generation source. The market imbalance, e. g., power excess or deficit, is regulated through the intra-day, or balancing market, where the selection of the generators is carried out by the SO. A non-profit partnership (NP) Market Council is responsible for developing the regulatory framework and for controlling compliance with the market rules. (NP Market Council, 2012).

Capacity trade is arranged differently for existing and for the planned generation (Gore et al., 2012; Boute, 2012). Existing generation facilities are subject to market-based selection. They submit their bids to competitive capacity auctions, where the Administrator of Trading System (ATS) selects the cheapest offers until the point, where the required capacity is filled for a year ahead period. The required capacity is defined by the System Operator (SO). Some other types of capacity compensation also exist in the Russian system, e.g., see (Gore et al., 2012; Kuleshov et al., 2012; NP Market Council, 2012), but these are left outside the scope of this paper.

New power generation projects that are related to the “historical” centralized investment plans are entitled to long-term regulated capacity agreements (Boute, 2015). The capacity price within such agreements is calculated for each project in accordance with the procedure defined by the legislation that is designed to cover investment costs plus some return (described in the next subsection).

The demand-side capacity price is defined as a weighted average of all supply-side capacity prices, in particular of the prices within the long-term agreements for new power generation projects and prices resulting from auctions for the existing power generation. Thus, capacity buyers automatically cover all paid capacity in the market, regardless of its source (Gore and Viljainen, 2014).

Participation in the wholesale electricity and capacity markets is obligatory for power generators with more than 25 MW installed capacity. Power plants with capacities between 5 and 25 MW may choose, whether they want to participate in the wholesale, or in the retail market. The capacity mechanism discussed in the next section is applicable only to the wholesale market.

2.1. The Russian capacity mechanism for conventional energy

The Russian capacity trade system originates from the privatization of the former quasi-monopolist ‘Unified Energy System of Russia’ (RAO UES) that until 2008 was the owner and the controller of the majority of electricity generation, transmission, distribution facilities, and the selling process in the Russian Federation. Investors who purchased RAO UES assets had to commit to the long-term, regulated power delivery contracts (and investments to back these up) and they were obliged to maintain a set minimum electricity production capacity, in order to ensure the reliability of the Russian electricity system (Boute, 2012). These contracts are called “Agreements for the Delivery of Capacity” (or “DPM” in Russian) and they are regulated by several Russian national laws (Government of the Russian Federation, 2010a, 2010b).

Project selection is carried out within annual auctions, where capital cost level is a competing criterion, meaning that the less expensive installations are chosen first. Power generators that win DPM at auctions are obliged, first of all, to construct and to commission a power plant in accordance with what is agreed in the contracted schedule and secondly, to be available to produce electricity thereafter and to follow the dispatching orders of the SO, in order to contribute to maintaining a balance in the network (International Finance Corporation, 2013; Government of the Russian Federation, 2010b). Violations of these obligations are punishable with fees set by the NP Market Council. With these conditions, the power generators are compensated for their capacity within the DPM term.

The capacity price is a subject to periodic adjustments that are based on changing market conditions. This is to ensure (guarantee) the coverage of the project investment cost and the operational costs of the power producer. Computed by the ATS, the capacity payments are paid to the producers monthly. This capacity agreement mechanism is meant to allow for easy access to the markets for new generation facilities that provide continuous electricity supply and that enhance the reliability of the supply of electricity on the long run. The aim of the capacity payments under a DPM is to assure a low-risk return for the energy investors.

The variable factors in the capacity price calculation for conventional energy are the rate of return and the rate of inflation. In addition, twice during the contract duration the capacity price is adjusted, based on the changes in the electricity prices. Determining the capacity price for conventional energy sources consists of the following four steps (Government of the Russian Federation, 2010a):

Step 1. Defining a "*guaranteed rate of return*" reflecting changes in the local risk-free rate;
Step 2. Calculating an "*expense share*" to be covered by capacity revenues, to reflect the share of revenues from electricity sales;
Step 3. Computing a *"capacity price component"* as a sum of a variable rate annuity of project capital costs and operating expenses (multiplied by the expense share);
Step 4. Calculating the *"capacity price"* by adding expected property tax expenses multiplied by the expense share to the capacity price component.

The capacity price is calculated annually separately for each month of the following year. Conventional energy types applicable for the capacity mechanism are thermal power (coal, gas), hydro, and nuclear power (the last two have longer than ten-year agreement durations). The details of the capacity price calculation are presented in detail in Appendix 1.

2.2. *The new Russian capacity mechanism for RE investments*

In addition to the "old" capacity mechanism described above, available for conventional power generation investments, Russia has since May 2013 instituted an extended "RE capacity mechanism" to accommodate for investments into wind, solar, and small hydro power (less than 25 MW) (Government of Russian Federation, 2015, 2013a, 2013b). Using a RE capacity mechanism to incentivize the naturally variable RE production may seem un-intuitive, as capacity mechanisms are commonly and typically used for conventional energy production. In fact, if a capacity based incentive mechanism intended for RE investments is not designed well, the outcome may be what is called the "steel-in the ground" effect (Boute, 2012): capacity is installed, but not actually used to generate power. The Russian RE capacity mechanism is very different from the RE support and capacity mechanisms used in other countries (International Finance Corporation, 2013).

The RE capacity mechanism includes a number of specific differences from the capacity mechanism for conventional energy. The most prominent differences are:

- The inclusion of the capacity factor (ratio between the produced electricity output over a given time period and a theoretical maximum output) into the remuneration calculation, in order to reflect electricity production performance from variable-output RE power generation;
- A local content requirement (the obligation to use a given share of nationally produced equipment and services) (Government of Russian Federation, 2013a);
- Reflecting the changing foreign currency exchange rate in the capacity price calculation by correcting the 'foreign' part of project capital expenses against the changes in the ruble exchange rate to the US dollar and to the euro during the project investment phase (this rule was introduced after the start the system, see (Government of Russian Federation, 2015));
- The non-fixed expense share. Changes in market conditions and in the capital cost trend of RE projects are updated and incorporated into it (Government of Russian Federation, 2013a);
- The dismissal of the requirement to follow SO's dispatching orders, except for the obligation to interrupt electricity production at the demand of the SO (Government of Russian Federation, 2013a). Violations to the rule carry a 25% fee of the monthly capacity price (NP Market Council, 2013).

The rules are furthermore adapted to the special features of RE investments, such as the fact that wind power cannot be produced, when there is not wind, or that solar power cannot be produced with no or very low irradiation.

With the above differences, the RE capacity price is calculated with the same general logic as the capacity price for conventional energy sources (Government of Russian Federation, 2015, 2013a, 2013b). The RE capacity price calculation can be expressed shortly in four steps as follows:

Step 1. The *guaranteed RE rate of return* is defined, it stands at a level of 14% for projects auctioned before 2016 and at 12% for the rest, similarly corrected to the change in national risk-free rate;
Step 2. The *RE expense share* is calculated as a function of the variable electricity prices, the local risk-free rate, the inflation, and the capital costs of earlier project bids (technology-wise);
Step 3. Computing *the RE capacity price component* is calculated as a sum of a variable rate annuity of project capital costs and operating expenses (multiplied by the expense share) with the following additions and/or changes:

- The capital cost level taken into consideration is not fixed, as it is for conventional energy, but takes values of project specific planned costs (lower remuneration for lower planned costs). Here one must remember that the project capital costs are what determines the success in the initial auction and their upper limit is fixed, see Appendix 2, Table 4.
- The capital cost level is adjusted by the localization coefficient, see Appendix 2, Table 6. After the investment is built and ready, there is a qualification procedure that verifies the achievement / non-achievement of the local content requirement. If localization is not fulfilled, the coefficient substantially decreases the CAPEX level used in the calculation of the incentive, and consequently the capacity price that is in effect for the duration of the capacity agreement.
- Exchange rate movements are taken into account to adjust 'foreign' share of capital expenses.

Step 4. The *RE capacity price*, is calculated by adding expected property tax expenses multiplied by the expense share to the capacity price component, but in contrast to conventional energy capacity price calculation, is corrected by a so-called "load coefficient" that reflects electricity production performance of the project (project specific). The load coefficient is in place to ensure the motivation for electricity production and to prevent the 'steel-in the ground' effect. If the achieved annual average capacity factor is lower than the set norm one the remuneration will be substantially reduced for the year ahead, see Appendix 2, Table 7. Overall, three separate RE capacity price levels are defined as a result of the electricity production performance: "full level", when the actual capacity factor is more than 75% of the norm one, "80% level", when the actual capacity factor is more than 50%, and "zero" remuneration otherwise.

The "default" or normative capacity factor values are separately calculated and set for each RE technology. The normative capacity factor of 27% that is set for wind farms, means approximately

7 m/s of average wind speed (European Wind Energy Association, 2009) that is quite common in the Russian territory according to the Global Average Wind Speed Map (Vaisala 3TIER, 2014). The normative capacity factor of 14% that set for solar power stations, is achievable with solar irradiation at the level of about 1500 kWh/m^2 per year (ABB, 2010), which corresponds to the irradiation in the areas of Southern Russia (Breyer and Schmid, 2010). The normative capacity factor set for hydro power approximately equals the capacity factor of small hydro plants operating in average flow conditions defined for the UK, on the level of 40% (British Hydropower Association, 2012). A detailed presentation of the RE capacity price calculation is presented in Appendix 2.

3. Numerical comparative study of the new Russian RE investment incentive policy

Policy influence on investors' behavior may be analyzed in different ways, one of the ways is numerical analysis that has been found to be a good way to corroborate and complete the findings of policy-desk type reviews (Azuela and Barroso, 2012). When numerical analysis is used, it can be done, e.g., by defining the key influential factors affecting the project and assessing their impact on the economic viability of the project. Here, we analyze the profitability of investments into the three different RE types that are covered by the Russian RE support mechanism with a model built for the purpose and also run a sensitivity analysis in order to see, how the profitability of a RE investment project changes, when the values of identified key factors change from -50% to $+50\%$ starting from a selected start-value.

For the purposes of comparative analysis between RE support schemes, we have calculated the sensitivity of a profitability of a model RE investment project to selected variables' values, when it is supported by the Russian RE capacity mechanism, and as a benchmark, when the same model project is supported by generic feed-in premium support mechanism. The feed-in premium scheme is chosen as a benchmark due to its simplicity, popularity in emerging markets, and because it was an initial choice also of the Russian government, even if such a policy never saw the light of day in Russia (International Finance Corporation, 2013). A feed-in premium level that gives an "equal to the RE capacity mechanism profitability" is used as a base level benchmark. In the construction of the model project, a number of choices with regards to the values used had to be made, but the same chosen values were consistently used in both the compared cases. The calculations were performed with MS Excel. The investment profitability analysis model used is presented in detail in (Kozlova, 2015).

3.1. Modeling assumptions

Electricity prices used in the analysis are the average day-ahead market prices, derived from the Russian Automated Information Data System on Electricity and Capacity Markets (NP Market Council, 2015). The capacity price calculation was made in accordance with the rules provided by the Russian legislation (Government of Russian Federation, 2013b, 2013a, 2015) and described above for all the three RE technologies. The aim is to analyze an "average" investment project, rather than a project located in a particular price zone (area in Russia). For this reason the nodal electricity price forecast for the capacity payment calculation is substituted by the average Russian day-ahead electricity market price. Data on the Russian 10-year government bond yield is used as the risk free rate and was obtained from Investing. com. Russian consumer price index data was procured from the Russian Federal State Statistics Service (Federal State Statistics Service, 2015). Values for the above three variables were, for the purposes of this illustration, projected until 2036 by using linear regression. The planned CAPEX is assumed to be at the limit level for each technology type for the commissioning year 2017, see Appendix 2, Table 4. The property tax expenses were defined based on the calculated project cash-flows and in accordance with the Russian Tax Code.

The model investment has a total installed capacity of 10 MW. The CAPEX used in the model is divided into two phases. The first phase, project development, takes place in 2015 and accounts for 5% of the investment cost and the second phase, construction, takes place in 2016 and accounts for 95% of the investment cost (UNEP and Aequero, 2011). For simplicity, production start is assumed to be on 01.01.2017 and the project lifetime is set at 20 years after the two-year investment phase. In this illustrative example we do not consider possible delays on project starts, such that have been evident, e. g., in association with many wind-power investments in Europe.

The capacity factors used for the three RE technologies are according to the fixed norm discussed above. The OPEX used is at the norm level, see (Government of Russian Federation, 2013a), and adjusted by the consumer price index change projections for each year. Taxes are calculated in accordance with the Russian Tax Code, the income tax rate is assumed to remain at 20%, the property tax rate used is 2.2%, and a straight-line depreciation for the whole project life-time is assumed.

The discount rate used was defined based on the data available from the Datastream service for several of the largest Russian energy companies, namely Inter RAO, OGK 2 owned by Gazprom, E. ON, Enel, and RusHydro that together with the state-owned non-listed RosAtom own more than half of all the electricity production capacity in the country. Their weighted average cost of equity is estimated to be at the level of 15.7%, the cost of debt at 9.5%, and the debt ratio at 40.5%, resulting in a total weighted average cost of capital equal to an estimated 12.4%. The discount rate is assumed to remain constant.

3.2. Results from the capacity price calculation

The results of the capacity price calculation, in accordance with the legislative rules and assumptions discussed above, show essential differences across the three technology types. As the RE capacity price calculation is based on the project expenses and on the expected production levels, the inherent discrepancy in technological features across the different technology types causes differences in the required return to cover the investment costs, and subsequently causes differences in the capacity prices. The RE capacity price calculation results with details are presented in Table 1.

Table 1 shows that all three technologies require a substantial share of costs to be covered by the support mechanism to be profitable. The "share of costs to be covered" is the share that will be covered by the RE capacity remuneration by the RE capacity mechanism, while the remaining share will come from electricity sales. For example, a solar power project that has the same CAPEX level as a wind power plant will receive less revenues from electricity sales due to its lower capacity factor. In comparison to small hydro, solar power requires roughly 25% less capital costs per MW, but the capacity factor is more than halved, leaving solar technology as the most expensive among the three technologies in terms of electricity production cost that is indicated in terms of the RE capacity price converted into rub./kWh. This means that solar power is the most expensive production alternative in relative terms, however, the situation may change over time, see, e.g., (Benson and Magee, 2014).

Table 1
RE capacity price calculation for the year 2017 for all three RE types.

#	Parameter	Wind	Solar	Hydro
1	Normative capacity factor	27%	14%	38%
2	CAPEX, thous. rub./kW	109.8	109.6	146.0
3	OPEX, rub./kW month	161	233	137
4	Property tax expenses, rub./kW year	1,392	2,318	3,132
5	Forecasting profit from electricity sales, rub./kW year	2,355	2,351	4,405
6	Gross required revenues, rub./kW year	23,729	24,546	30,629
7	Share of costs needed to be covered	86%	93%	85%
8	RE capacity price rub./kW month	1,728	2,081	2,202
9	**RE capacity price rub./kW year**	**20,742**	**24,978**	**26,423**
10	*RE capacity price converted to rub./kWh*	*8.8*	*20.4*	*7.9*

3.3. Sensitivity analysis of RE investment profitability under two different support mechanisms

To further study the capacity mechanism for RE investments, we analyze the sensitivity of the model project profitability to a number of contributing factors and compare the results with the results received, ceteris paribus, under a generic feed-in premium scheme. We found that the three technologies are very similar in terms of the sensitivity of profitability to the contributing factors. Minor differences are however found and they are associated with initial differences in capital costs, capacity factors, and other technology-specific features. For the purposes of this illustration we only show the case of a wind power project and use it as the basis for examining the differences between the sensitivity of the profitability under the two different RE support mechanisms. The results of the sensitivity analysis are presented in Fig. 1 for the generic feed-in premium case (the left graph) and for the Russian RE capacity mechanism (the right graph).

Visual inspection reveals that generally speaking the project profitability under the Russian RE capacity mechanism seems to be less sensitive to the contributing factors, than under the generic feed-in premium scheme. A notable exception is the case, where the RE capacity factor falls below the threshold that fully cuts out the incentive payments. Table 2 summarizes the sensitivity analysis results.

Under the Russian RE capacity mechanism, project profitability is less sensitive to electricity price and to changes in the inflation, though changes in the CPI seem to have a moderate effect on profitability under both incentive systems. Changing the risk-free rate has an effect under the Russian RE capacity mechanism, as the RE capacity payments depend on the level of the risk-free rate. Respectively, there is no effect under the feed-in premium that is, profitability is insensitive to changes in the risk-free rate under the feed-in premium scheme. It needs to be noted that project-specific debt-levels play a role here, as in reality the risk-free rate is often connected to the cost of debt. In broad strokes, "external" factors' influence on the project profitability is low for both cases – this is expected, as it is the main idea behind these RE incentive systems.

Project-related "internal" factors play a significant role for project profitability under both mechanisms. It is natural that when capital costs increase project profitability suffers. The capacity factor, or in other words the amount of energy produced of the total production capacity, is directly (linear relationship) affecting the feed-in premium case, and both, directly and in-directly through the load coefficient used in the capacity price calculation affecting the capacity mechanism case – capacity mechanism puts a "tougher incentive" in place for producing electricity.

Operational costs have a direct and a clear relationship of the same size to profitability in both cases, the better the project can manage the operational costs, the better is the profitability. For both cases the sensitivity of project profitability to the discount rate is considerable, and accentuated by the long project lifetime – what is interesting and important to notice is that the RE incentive schemes actually work to reduce the discount rate and therefore, also in this way, incentivize investment into RE production.

Falling outside Fig. 1, but tested with the investment model the "local content" factor, if not fulfilled, substantially reduces capacity payments for the whole contract term, making RE investment under the capacity mechanism irreversibly sunk.

4. First results of the Russian RE capacity mechanism implementation

So far, three RE power generation project auctions have been conducted since the year 2013. The auction has been open for projects commissioned in a four-year ahead window after the year of auction, e.g., in 2013 projects were selected with starting dates for the years 2014–2017. Table 3 summarizes results of all three auctions and presents both the target and the amount of selected to-be-installed capacity.

The auction results reveal that the RE capacity mechanism seems to be working well for solar PV investments, with the full volume of target capacity selected and competition in place. In contrast, wind and small hydro power investors seemingly face some barriers and are reluctant to participate. There may be several reasons behind this situation.

Poor results of the first auction, especially for the first year 2014, may be explained by a too short period (a couple of months) between the policy introduction and the deadline for bid submission. Investors simply were not able to prepare all the required documentation. For 2014 and 2015 the observed shortage of wind and small hydro power bids is attributable to the strict localization requirements and the capital cost limits. In addition, the devaluation of the ruble has made it more difficult to meet the capital cost limit calculated in rubles for technologies that are more dependent on imports payable in foreign exchange. Projects have

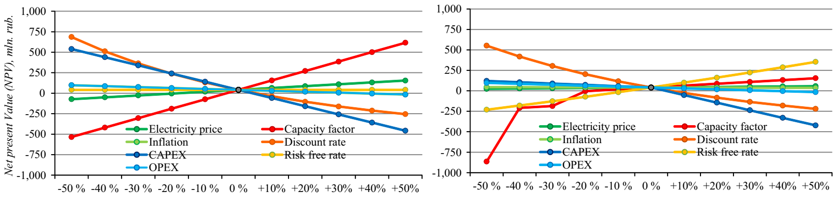

Fig. 1. Model project NPV sensitivity to selected factors' values under a feed-in premium scheme (left) and the Russian RE capacity mechanism (right).

Table 2
Sensitivity of project NPV to selected factors' values.

Factor	Under the feed-in premium	Under the capacity mechanism
Electricity price	Moderate sensitivity.	Compensation effect causes very low sensitivity.
Inflation (CPI)	Low sensitivity.	Compensation effect causes very low sensitivity.
Risk free rate	No sensitivity.	NPV becomes sensitive to the risk free rate, due to the fixed discount rate.
CAPEX	High sensitivity–linear relationship.	Sensitivity to CAPEX changes according to the amount of CAPEX, potential from savings muffled.
RE capacity factor	High sensitivity–linear relationship.	Target RE capacity factor and the two thresholds cause the sensitivity to change stepwise.
OPEX	Low-to-moderate sensitivity.	Low-to-moderate sensitivity.
Discount rate	High sensitivity.	High sensitivity.

Table 3
Auction results, MW (auctions 2013–2015).

Technology	Capacity	2014	2015	2016	2017	2018	2019
Wind	target	100	250	250	500	750	750
	selected	0	51	50	90	0	0
	%	0%	20%	20%	18%	0%	0%
Solar PV	target	120	140	200	250	270	270
	selected	35.2	140	199	255	285	270
	%	29%	100%	100%	102%	106%	100%
Small hydro	target	18	26	124	124	141	159
	selected	0	0	0	20.64	0	49.8
	%	0%	0%	0%	17%	0%	31%

most likely been unable to switch to Russian national manufacturers, simply due to their scarcity. Investors could not meet the RE capacity mechanism requirements of localization and invoked Russian government to revise the rules. As the result of negotiations between investors and policymakers, amendments to the RE capacity mechanism were introduced right before the third auction in November 2015 (Government of Russian Federation, 2015).

The said amendments include several important changes, designed to remove the above mentioned barriers to investment. Localization requirement and capital cost limit have been "softened" for wind power projects. RE capacity remuneration for small hydro power investment is increased by introducing an additional coefficient, see Appendix 2, while the localization requirement and the CAPEX limits remain on the same level as previously for this technology. To resolve the issue with currency volatility, the correction of the capital costs limit (as well as project-specific planned CAPEX) is introduced and takes into account ruble value movements for the 'foreign' part of the CAPEX, during the investment phase. Together with the development of the Russian national RE manufacturing sector, these changes are expected to resolve the current problems.

5. Conclusion and policy implications

Enacted in 2013, the Russian renewable energy support mechanism is based on capacity remuneration and thus has a different starting point for a RE investment incentive mechanism than the commonly used incentive systems for renewable energy used. The RE capacity mechanism combines a "guarantee" of a set level of return on investment for RE power generation investments, shielding their profitability from changing market factors, while including a number of codified requirements on electricity production, local content, and on capital expenditure.

The studied RE capacity mechanism represents the first supporting policy for renewable energy put in action in Russia. Being an extension of the pre-existing capacity market rules, the RE support mechanism has been naturally embedded into the existing Russian energy market system. On one hand it is an easy-to-implement solution for policymakers, and on the other a not fully unfamiliar scheme for the existing market participants. What can be said is that the RE capacity pricing under the mechanism is rather complex and one that requires expertise in understanding the effects it has on investment profitability. This paper has "opened up" the complexity of the mechanism and of the RE capacity pricing.

RE remuneration is paid as capacity price to selected projects within the framework of long-term contracts. The capacity price is updated on a regular basis within each agreement to reflect the changing market environment and the performance of the project, in accordance with the set procedures. The RE mechanism is designed to make RE project profitability rather independent from project external factors, such as market prices for electricity, inflation, and interest rates. Our analysis shows that it can be said to perform rather well in that respect. Project internal factors, such as capital costs, operating costs, and the RE capacity factor remain un-hedged by the mechanism. The mechanism restricts project capital costs to control the overall burden on the market system, imposes localization requirement to push the Russian national manufacturing sector, and penalizes for low levels of electricity production. Our illustrative numerical analysis and the connected sensitivity analysis on a model investment show that the different requirements set by the mechanism are important from the point of view of RE project profitability. Especially, what is found is that project underperformance, reflected as low electricity production, capital costs overspending, and failing the localization requirement is the most important single issue to consider with regards to the mechanism, when RE investments are planned.

The capacity remuneration grows with growing interest rates on the market, allowing investors to sustain higher financing costs. This effect provides investors with considerable risk reduction that is not offered by any other RE supporting policy type, however the adjustability of the capacity price prevents investors from fully benefiting from very favorable market conditions and thus shields the capacity buyers.

The complexity of the RE mechanism, including the high level of controllability of the policy puts a heavy responsibility on the policymakers and policy controllers to estimate the used values in a way that creates a favorable market environment for investment. A too loose set of requirements may decrease the policy cost-efficiency, while a too strict set may work to hinder investments, as already has been learned from the experience with wind and small hydro power.

In an international and an emerging economies context the Russian RE capacity mechanism takes a special place among the existing RE policy types. It is clearly different from the three main types of RE support mechanisms used in emerging economies. The results from the first three implemented project auctions show that the mechanism has been a partial success. It remains to be seen, if the enacted changes boost investment into RE in Russia also within the wind power and small hydropower technologies.

As a final note on policy flexibility, in terms of the Russian RE support mechanism, it can be observed that as each supported project is a specific case and represented by a specific contract, changing any or all aspects of the national level support for renewable energy production in Russia is not conditioned in any way by the existing policy. Each contracted project is singular and can co-exist with any kind of new system irrespective of its provisions. This means that migration away from the existing mechanism is "easy" as it is not likely to cause resistance by the existing support contract holders.

Future research on the topic will include using simulation-based techniques to deepen the investment analysis. More detailed "real world" and area specific analysis is also something that will benefit the industry. Comparative analysis of the Russian capacity mechanism with a broader set of existing and in detail modeled RE policies worldwide will benefit policymakers. It will also make sense to broaden the research scope to include the newly introduced Russian renewable energy premiums scheme for retail markets that focuses on medium-scale RE projects.

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Appendix 1. Capacity price calculation for conventional energy

Step 1. A "*guaranteed rate of return*" is calculated, based on an initially set level of 14–15% (for different groups of participants) and corrected for changes in a reference risk-free rate, for which the yield of the Russian state long-term obligations is used as the reference (only notes with maturities from 8 to 10 years are appropriate for the calculation, see (The Ministry of Economic Development and Trade, 2010)). The following formula is used:

$$R_i = \frac{(1 + R_b)*(1 + Rf_i)}{(1 + Rf_b)} - 1 \approx R_b + \Delta Rf, \tag{1}$$

where R_i is the guaranteed rate of return for i year (from 1 to 15);.

R_b is base guaranteed rate of return (=14–15%);

Rf_b is base risk free rate=8.5%;

Rf_i is risk free rate for i year (inflation correction).

The guaranteed rate of return is effectively a minimum, or a "floor rate" established for the return of these investments and is paid, if other factors such as capital and operating costs are within set norms.

Step 2. As power investment projects receive revenues also from electricity sales, the share of the costs to be covered by the capacity payments, the "*expense share*", is separately established. The expense share is based on the expected revenues from the electricity market that are dependent on the electricity production profile of the investment. Furthermore, it is a function of the capital (CAPEX) and the operational expenditures (OPEX). The values of the inputs to the expense share calculation are specified and remain fixed for all producers (Government of the Russian Federation, 2010a). To avoid the capacity price being out of date with market conditions, the OPEX value is adjusted by inflation for each year of the contract, and the expense share is adjusted for electricity price changes twice during the contract duration (on the 4th and the 7th year of the contract).

Step 3. A "*capacity price component"* is calculated. This includes first arriving at an "adjusted CAPEX" for the first year of the capacity contract:

$$CAPEX_{adj}=CAPEX*E*(1+R_{-1})^{N_{st}} \tag{2}$$

where *CAPEX* is defined separately for each technology type, and multiplied by a number of fixed coefficients, see (Government of the Russian Federation, 2010a) and where.

E is the expense share defined in step 2;

R_{-1} is R defined in (1) *for* $i=-1$;

N_{st} is a constant; specified for each technology type separately;

Then the adjusted CAPEX is converted to annual payments with a variable interest rate. The payback period is assumed to be 15 years and thus capacity price is calculated for 15 years. However, since the contract duration is set at 10 years, the capacity price calculated for years 11–15 is settled within the last three years of the ten year capacity contract. We remark that this is a point of discussion in Russia and the contract term may in the future be extended to fifteen years. The payment of the principal and the remaining principal are defined as (principal implies adjusted CAPEX):

$$Pp_i=\frac{Rp_i*(k-1)}{(k^{16-1}-1)}, \tag{3}$$

$$Rp_i=Rp_{i-1}-Pp_{i-1}+(R_{i-1}-R_{i-2})*(1 + R_{i-1})*Rp_{i-1}, \tag{4}$$

where Pp_i is the annual principal payment;.

Rp_i is the remaining principal (for $i=1$ $Rp_1=CAPEX_{adj}$);

k is equal to 1.19 for the first price zone and 1.16 for the second price zone.

Finally, the capacity price component is defined as a percentage of the remaining principal (adjusted on the income tax rate), plus the principal payment itself, and plus the operating expenses:

$$CP_{comp}=Rp_i*\frac{R_{i-1}}{1 - r_{inc_{tax}}}+Pp_i+OPEX*E, \tag{5}$$

where CP_{comp} is the capacity price component;.

Rp is a result from (4);

r_{inctax} is an income tax rate equal to 0.2 (or 20%);

Pp is a result from (3);

OPEX is an inflation adjusted *OPEX*, specified in (Government of the Russian Federation, 2010a) separately for each technology type;

E is expense share defined in step 2.

Step 4. The capacity price is derived as the sum of the *capacity price component*, CP_{comp}, and property tax expense multiplied by the *expense share*:

$$CP=CP_{comp}+T_{pr}*E, \tag{6}$$

where CP is capacity price;.

CP_{comp} is defined in (5);

T_{pr} is the average property tax expenses,

E is the expense share defined in step 2;

Appendix 2. Capacity price calculation for renewable energy

Step 1. Defining rate of return with the same formula (1) with the only difference, that basic return is set as 14% for project that for auctioned before 2016 and 12% for the rest.

Step 2. The expense share to be covered is determined for the "average RE power generator" each year of the capacity contract tenor. Preliminary expense share is calculated using the following formula:

$$E_{0_i}=\frac{Re_{\ i}}{12*Rc_i}, \tag{7}$$

$$E_{1_i}=\begin{cases} 0, if E_{0_i}\geq 1 \\ 1-E_{0_i},\ if\, 0>E_{0_i}>1 \\ 1, if E_{0_i}\leq 0 \end{cases} \tag{8}$$

where E_{0_i} is the ratio of expected revenues from electricity sales / required revenues to cover all costs;

E_{1_i} the preliminary expense share;

Re is the expected revenue from the electricity sales;

Rc is the expected revenue from the capacity sales.

The above means that if the electricity price received from the market is high enough to cover the minimum guaranteed return for RE power generation investments, the paid incentive capacity price is zero. In reality the situation is hypothetical at best.

To determine the final expense share value E for each year of the agreement, the average of the actual and the following year's preliminary expense share (8) is calculated. The expense share for uneven years of the contract duration is set to be equal to this average, and for even years to the value calculated for the previous year.

The expected revenue from capacity sales, for the purpose of expense share calculation, is determined in accordance with the third (next) step of the calculation process with the following assumptions: expense share (E) is equal to 1 and the capital expenditures (CAPEX) are defined as the weighted average of CAPEX of the bids submitted to the capacity price auction (separately for each technology). In other words, step 3 is actually repeated twice: once for the 'average project', to calculate the expense share, and once to calculate the actual capacity price for a specific project.

The revenue from the electricity sales calculation is done as follows:

$$Re_i=cf_i*hours*\left(\frac{P_i}{k}-C_{pr_i}\right), \tag{9}$$

where cf is a normative capacity factor (Table 7);.

$hours$ is a quantity of hours in a year i;

P is a day-ahead electricity market price defined in (10);

k is a coefficient of power consumption for own needs that is 1.005 for all RE types;

C_{pr} is inflated variable cost of production initially defined for wind, solar, and hydro as 1, 1, and 10 rub/MWh respectively;

The day-ahead electricity price is forecasted as a weighted average of the previous years' prices of all nodes, corrected with a growth rate. The following formula is used:

$$P_i=\frac{\sum_h \sum_q P_{q,h}*Prod_{q,h}}{\sum_h \sum_q Prod_{q,h}}*\prod_{Y=X}^{i} g_Y^C, \tag{10}$$

where h is an hour of previous year;.

q is a node;

$P_{q,h}$ is the day ahead electricity price for a particular node and hour (time);

$Prod_{q,h}$ is the production volume for a particular node and an hour;

g_Y^C is a forecasted growth rate of prices of gas (for the first price zone) or of coal (for the second price zone) for year Y;

Step 3. Calculating the capacity price component for RE has a similar logic to the "same" calculation for conventional energy, but with some important differences. Firstly, capital expenditure level is not fixed, but the limit is set separately for each technology and for each year, and the set values decrease with time, see (Government of Russian Federation, 2013b, 2013a). Table 4 illustrates this issue further.

Table 4
CAPEX limit and OPEX norm (set value).

Technology type	CAPEX limit, thous. rub./kW				OPEX norm, rub./kW pm
	2016	2017	2018	2019	
Wind	109.9	109.8	109.7	109.6	118
Solar	111.8	109.6	107.4	105.3	170
Hydro	146.0	146.0	146.0	146.0	100

RE projects are "capped" with the values in Table 4 that is, projects with planned CAPEX higher than the set limits cannot participate in the auction. If the planned CAPEX is lower than the limits given in Table 4 the lower figure is used in the calculation of the capacity price. Hence, the lower the planned CAPEX is, the lower is the calculated capacity price, and this causes a clear disincentive to reduce the CAPEX level. To keep the motivation among investors to reduce the CAPEX, the CAPEX is set as the object on which the competing projects ranked on: only a selected number of projects, with the lowest planned CAPEX that satisfy the target selection volume, become eligible for the capacity agreement (incentive system). The target installed capacity for each year is presented in the Table 5 (Government of Russian Federation, 2013b).

There are three coefficients that are used in further conditioning the planned CAPEX, when the capacity price calculation is performed. The first and the more important one is the "local content" coefficient that is a requirement of acquiring a set part of the services and equipment used in the investment such that they are produced locally in Russia (Table 6) (Government of Russian Federation, 2013a). The projects with planned localization lower than the set target are rejected.

The second coefficient reflects changes of the 'foreign' share of capital expenses due to exchange rate movements (Government of Russian Federation, 2015):

$$k=loc_{target}+\left(1-loc_{target}\right)*k_{exch.r.} \tag{11}$$

where loc_{target} is target localization percentage.

$k_{exch.r.}$ is coefficient reflecting ruble value change against US dollar and euro during the investment period (6 months period 12 months prior commercialization date for solar power, 12/18 for wind and 36/42 for hydro). A cap is set $k_{exch.r.MAX}=3$.

The third coefficient applied to the CAPEX calculation reflects the profits from the wholesale market after the breakeven point, and before the end of the economic life of the project. This coefficient is fixed and equal to 0.90 for wind and hydro power, and 0.99 for solar power.

Table 5
Target installed capacity, MW.

Technology type	2014	2015	2016	2017	2018	2019	2020	Total
Wind	100	250	250	500	750	750	1000	3600
Solar	120	140	200	250	270	270	270	1520
Hydro	18	26	124	124	141	159	159	751

Table 6
Local content requirement.

Technology type	Target local content requirement				Coefficient	
	2016	2017	2018	2019	Target achieved	Target not achieved
Wind	25%	40%	55%	65%	1.00	0.45
Solar	70%	70%	70%	70%	1.00	0.35
Hydro	45%	45%	65%	65%	1.00	0.45

The CAPEX corrected on exchange rate movements and adjusted with these two coefficients can be calculated as (2)

$$CAPEX_{adj}=CAPEX{*}E_1{*}(1+R_{-1})^f \tag{12}$$

where *CAPEX* is the planned CAPEX corrected on exchange rate movements and multiplied by the two coefficients;.

E_1 is the expense share, defined in step 2 for the first year of capacity agreement;

R_{-1} is R defined in (1) for $i=-1$;

N_{st} is a constant that is separately given for each technology type;

f is equal 1 for wind and solar power and 1.5 for hydro (introduced with Government of Russian Federation (2015)).

The adjusted CAPEX is converted into annual payments by means of a variable rate annuity similar to the capacity price for conventional energy calculation, but with a small change. The principal payment calculation for the RE investments uses a variable rate of return calculated in Eq. (1), this is different from using a fixed rate in the conventional energy capacity price calculation, where only the remaining principal is calculated with a variable rate of return.

$$Pp_i=\frac{Rp_i{*}R_{i-1}}{((R_{i-1}+1)^{16-1}-1)}, \tag{13}$$

where Pp_i is the principal payment;.

Rp_i is the remaining principal, for $i=1$ $Rp_1=CAPEX_{adj}$.

The remaining principal is calculated exactly in the same way as for conventional energy presented in (4).

The capacity price component is defined as follows:

$$CP_{comp}=\frac{Rp_i{*}\frac{R_{i-1}}{1-r_{inctax}}+rPp_i}{12}+OPEX{*}E_i, \tag{14}$$

where CP_{comp} is capacity price component;.

Rp_i is the remaining principal;

Pp_i is the principal payment;

$R_{i\text{-}1}$ is the rate of return defined in (1);

r_{inctax} is an income tax rate equal to 0.2;

OPEX is an inflation adjusted OPEX norm specified in Table 4,

E_i is the expense share defined by (7 and 8).

Step 4. The capacity price for RE investments is defined as the sum of the capacity price component calculated in step 3 and the property tax expenses, multiplied by the expense share defined in step 2:

$$CP=CP_{comp}+T_{pr}/12{*}E_i, \tag{15}$$

Where *CP* is the capacity price;.

CP_{comp} is defined in (13);

T_{pr} *is* the average property tax,

E_i *is* the expense share defined in step 2;

After this, a fixed coefficient of "energy for own needs" equal to 1.005 for all types of RE sources is used to multiply the result.

What still remains is the "load" coefficient. It is a multiplier that is used in the calculation of the capacity price for each year. The load coefficient is in place to ensure the motivation for electricity production and to prevent the 'steel-in the ground' effect, see (Government of Russian Federation, 2013a). See Table 7 for the load coefficient calculation.

Table 7
Load coefficient formation.

Normative capacity factor		Load coefficient formation	
Technology type	Normative capacity factor	Condition[a]	Load coefficient
Wind	27%	$F \le 0.5$ N	0.0
Solar	14%	$0.5\text{ N} < F \le 0.75$ N	0.8
Hydro	38%	$F > 0.75$ N	1.0

[a] F is factual average capacity factor achieved in the previous year and N is normative one.

An example of how the load coefficient works: if the capacity factor achieved in the previous year for a wind farm was lower than 13.5% (=27%*0.5), the capacity payments for this year would turn to zero; if capacity factor was between 13.5% and 20.25% (=27%*0.75), the capacity payments would be multiplied by 0.8; and only if the capacity factor was higher than 20.25%, the capacity payments would be paid in full.

References

ABB, 2010. Technical Application Papers No.10 Photovoltaic Plants. Available at: ⟨http://www04.abb.com/global/seitp/seitp202.nsf/c71c66c1f02e6575c125711f004660e6/d54672ac6e97a439c12577ce003d8d84/$file/vol.10.pdf⟩ [October 6, 2015].

Apergis, N., Payne, J.E., 2011. The renewable energy consumption–growth nexus in Central America. Appl. Energy 88, 343–347.

Apergis, N., Payne, J.E., 2010. Renewable energy consumption and growth in Eurasia. Energy Econ. 32, 1392–1397.

Azuela, G.E., Barroso, L.A., 2012. Design and performance of policy instruments to promote the development of renewable energy: emerging experience in selected developing countries, World Bank Publications.

Beck, F., Martinot, E., 2004. Renewable energy policies and barriers. Encycl. Energy 5, 365–383.

Benson, C.L., Magee, C.L., 2014. On improvement rates for renewable energy technologies: Solar PV, wind turbines, capacitors, and batteries. Renew. Energy 68, 745–751.

Boute, A., 2016. Off-grid renewable energy in remote Arctic areas: An analysis of the Russian Far East. Renew. Sustain. Energy Rev. 59, 1029–1037.

Boute, A., 2015. Russian Electricity and Energy Investment Law.

Boute, A., 2013. Renewable energy federalism in Russia: regions as new actors for the promotion of clean energy eqt005. J. Environ. Law, 05.

Boute, A., 2012. Promoting renewable energy through capacity markets: An analysis of the Russian support scheme. Energy Policy 46, 68–77.

Breyer, C., Schmid, J., 2010. Population density and area weighted solar irradiation: global overview on solar resource conditions for fixed tilted, 1-axis and 2-axes pv systems. Horizon, 1.

British Hydropower Association, 2012. A Guide to UK Mini-Hydro Developments Plants. Available at: ⟨http://www.british-hydro.org/Useful_Information/A%20Guide%20to%20UK%20mini-hydro%20development%20v3.pdf⟩ (October 6, 2015).

Central Intelligence Agency, 2014. The World Factbook. Country Comparison. Electricity production. Available at: ⟨https://www.cia.gov/library/publications/the-world-factbook/rankorder/2232rank.html⟩ (October 6, 2015).

del Río, P., Cerdá, E., 2014. The policy implications of the different interpretations of the cost-effectiveness of renewable electricity support. Energy Policy 64, 364–372.

del Río, P., Linares, P., 2014. Back to the future? Rethinking auctions for renewable electricity support. Renew. Sustain. Energy Rev. 35, 42–56.

European Wind Energy Association, 2009. Wind Energy the Facts. Technology. Available at: ⟨http://www.wind-energy-the-facts.org/images/chapter1.pdf⟩ (October 6, 2015).

Fais, B., Blesl, M., Fahl, U., Voß, A., 2014. Comparing different support schemes for renewable electricity in the scope of an energy systems analysis. Appl. Energy 131, 479–489.

Federal State Statistics Service, 2015. Consumer Price Index (Available only in Russian). Available at: ⟨http://www.gks.ru/free_doc/new_site/prices/potr/tab-potr1.htm⟩ (October 6, 2015).

Frankfurt School UNEP Collaborating Centre, Bloomberg New Energy Finance, 2015. Global Trends in Renewable Energy Investment 2015.

Gore, O., Viljainen, S., 2014. Challenges of cross-border trade between two markets with different designs, In: European Energy Market (EEM), 2014 11th International Conference on the, Anonymous IEEE, pp. 1–5.

Gore, O., Viljainen, S., Makkonen, M., Kuleshov, D., 2012. Russian electricity market reform: Deregulation or re-regulation? Energy Policy 41, 676–685.

Government of the Russian Federation, 2010a. 13 April 2010 Decree No.238 on the Determination of Price Parameters for the Trade in Capacity.

Government of the Russian Federation, 2010b. 27 December 2010 Decree No.1172 Approving the Wholesale Market Rules.

Government of Russian Federation, 2013a. 28 May 2013 Decree #449 on the Mechanism of promoting the Use of Renewable Energy in the Wholesale Market of Electric Energy and Power.

Government of Russian Federation, 2013b. 28 May 2013 Resolution #861-r on amendments being made to Resolution #1-r 8.01.2009 on the main directions for the state policy to improve the energy efficiency of the electricity sector on the basis of renewable energy sources for the period up to 2020.

Government of Russian Federation, 2015. 10 November 2015 Decree #1210 on the Introduction of Amendments to the Certain Legislative Acts Regarding the Use of Renewable Energy Sources in the Wholesale Electricity and Capacity Market.

Held, C., Voss, J.O., 2013. Legal limits for electricity capacity markets in the EU and Germany. Renew. Energy Law Policy Rev. 4, 245–253.

Hobbs, B.F., Hu, M., Iñón, J.G., Stoft, S.E., Bhavaraju, M.P., 2007. A dynamic analysis of a demand curve-based capacity market proposal: the PJM reliability pricing model. Power Syst. IEEE Trans. 22, 3–14.

International Energy Agency, International Renewable Energy Agency, 2014. IEA/IRENA Global Renewable Energy Policies and Measures Database. Available at: ⟨http://www.iea.org/policiesandmeasures/renewableenergy/⟩ [October 6, 2015].

International Finance Corporation, 2013. Russia's New Capacity-based Renewable Energy Support Scheme. An Analysis of Decree No. 449. Available at: ⟨http://www.ifc.org/wps/wcm/connect/f818b00042a762138b17af0dc33b630b/Energy-Suppor-Scheme-Eng.pdf?MOD=AJPERES⟩ (October 6, 2015).

International Finance Corporation, 2011. Renewable Energy Policy in Russia: Waking the Green Giant. Available at: ⟨http://www.ifc.org/wps/wcm/connect/6239e00040c80fcdb865bd5d948a4a50/Green+Giant_Eng.pdf?MOD=AJPERES⟩ (September 2, 2015).

Kozlova, M., 2015. Analyzing the effects of the new renewable energy policy in Russia on investments into wind, solar and small hydro power. Lappeenranta University Of Technology., Lappeenranta, Finland, p. 104.

Kuleshov, D., Viljainen, S., Annala, S., Gore, O., 2012. Russian electricity sector reform: Challenges to retail competition. Uti. Policy 23, 40–49.

Lund, P.D., 2007. Effectiveness of policy measures in transforming the energy system. Energy Policy 35, 627–639.

Martinot, E., 1999. Renewable energy in Russia: markets, development and technology transfer. Renew. Sustain. Energy Rev. 3, 49–75.

Martinot, E., 1998. Energy efficiency and renewable energy in Russia: Transaction barriers, market intermediation, and capacity building. Energy Policy 26, 905–915.

Maurer, L.T.A., Barroso, L.A., 2011. Electricity Auctions. An Overview of Efficient Practices. Available at: ⟨http://www.ifc.org/wps/wcm/connect/8a92fa004aabaa73977bd79e0dc67fc6/Electricity+and+Demand+Side+Auctions.pdf?MOD=AJPERES⟩ (October 6, 2015).

NP Market Council, 2015. Automated Information Data System on Electricity and Capacity Markets (Available only in Russian). Available at: http://www.ais.np-sr.ru/information/IASE_0V_R0_CONSUMPTION#прогноз_цен_РРЭ (October 6, 2015).

NP Market Council, 2013. 16 December 2013 Proceedings on the introduction of amendments to the Contract of joining the Trading System of the Wholesale Market.

NP Market Council, 2012. Wholesale Market. Available at: ⟨http://www.en.np-sr.ru/abouttheelectricityindustry/electricityandcapacitymarkets/wholesalemarket/#3⟩ [March 12, 2016].

Pegels, A., 2010. Renewable energy in South Africa: Potentials, barriers and options for support. Energy Policy 38, 4945–4954.

REN21, 2015. Renewables 2015 Global Status Report. Available at: ⟨http://www.ren21.net/wp-content/uploads/2015/07/REN12-GSR2015_Onlinebook_low1.pdf⟩ [August 15, 2015].

Russian Ministry of Energy, 2013. Power Industry Basic Indicators (available Only in Russian). Available at: ⟨http://www.minenergo.gov.ru/activity/powerindustry/basic_indicators/⟩ (October 6, 2015).

Salim, R.A., Rafiq, S., 2012. Why do some emerging economies proactively accelerate the adoption of renewable energy? Energy Econ. 34, 1051–1057.

Tennbakk, B., Lafitte, J., Capros, P., Delkis, C., Tasios, N., Zabara, M., et al., 2013. Capacity Mechanisms in Individual Markets within the IEM. Available at: ⟨https://ec.europa.eu/energy/sites/ener/files/documents/20130207_generation_adequacy_study.pdf⟩ (October 6, 2015).

The Ministry of Economic Development and Trade, 2010. 26 July 2010 Order No. 329.

Timilsina, G.R., Kurdgelashvili, L., Narbel, P.A., 2012. Solar energy: Markets, economics and policies. Renew. Sustain. Energy Rev. 16, 449–465.

UNEP, Aequero, 2011. Catalysing Early Stage Investment. Addressing the Lack of Early-Stage Capital for Low-Carbon Infrastructure in Developing Economies. Available at: ⟨http://www.scaf-energy.org/news/pdf/Catalyzing%20Early%20Stage%20Investment.pdf⟩ (October 6, 2015).

Vaisala 3TIER, 2014. Global Mean Wind Speed at 80m. Available at: ⟨http://www.vaisala.com/VaisalaImages/ERG/Vaisala_global_wind_map.pdf⟩ (October 6, 2015).

Vasileva, E., Viljainen, S., Sulamaa, P., Kuleshov, D., 2015. RES support in Russia: Impact on capacity and electricity market prices. Renew. Energy 76, 82–90.

Zhang, H., Li, L., Cao, J., Zhao, M., Wu, Q., 2011. Comparison of renewable energy policy evolution among the BRICs. Renew. Sustain. Energy Rev. 15, 4904–4909.

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Real option valuation in renewable energy literature: research focus, trends and design

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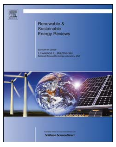

Real option valuation in renewable energy literature: Research focus, trends and design

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ABSTRACT

In light of intensive development of the renewable energy (RE) sector, a growing number of academic papers address the complexity of RE investment planning and valuation. To take account of the high-risk profile and irreversibility of RE investments, researchers have resorted to sophisticated real options (RO) approaches that enable flexibility to be incorporated into project design in the face of an uncertain environment. The variety of different frameworks and models adopted as well as a lack of aggregated analysis of the field suggest a need for a critical review of RO methodology and design in RE assessment. This study describes the research focus, trends and design found in contemporary academic literature devoted to RE valuation with a RO approach. Particular attention is given to RO in project and policy design. The results give a comprehensive picture of existing research on the topic, thus providing researchers with a solid foundation for further study and indications of directions for future development. Furthermore, the findings provide policymakers and project planners with valuable insights into key aspects of RE project and policy design.

1. Introduction

Climate change issues are receiving urgent attention from the global community, and mitigation of and adaptation to climate change is an essential part of national agendas. Among other measures, renewable energy (RE) development has considerable potential to reduce greenhouse gas emissions by replacing conventional fossil fuel based energy.

Global annual investment in renewable energy reached $286 billion in 2015, starting from four times less a decade earlier [1]. Such rapid growth owes a great deal to the widespread introduction of policies supporting renewable energy, which have been implemented in 146 countries around the world [2]. Nevertheless, investors in RE projects encounter many risks and uncertainties that have to be adequately evaluated and addressed to ensure investment profitability. RE projects in the power generation sector are characterized by relatively high upfront investment costs and lower operation and maintenance expenditures compared to conventional energy projects, which implies a high degree of irreversibility in the investment and has invoked a search for flexibility in project design. Projects in the bioenergy sector, in contrast, possess operational flexibility, seen in an ability to change raw material and fuels used, or an ability to modify output products in response to the volatile price environment. These features of RE projects have prompted decision-makers and researchers to employ real options (RO) approaches, which are able to value both uncertainty and flexibility in investment valuation and planning.

Several published reviews explicitly demonstrate a number of models and approaches to RO valuation design for renewable energy investments [3–6]. These papers, however, provide only a fragmentary overview, limiting their samples to a few selected studies and focusing on specific aspects of RE valuation. Moreover, a substantial number of papers published in recent years are absent from these reviews.

Therefore, in order to provide a more comprehensive picture of current research focuses, trends and designs, the current work aims to present a more thorough review of academic papers that apply RO approaches to renewable energy projects or policy valuation. The objectives of the paper are to review the body of scientific literature that considers real options approaches to renewable energy projects or policies, to describe the general research focus and trends in the field, to provide a comprehensive overview of the design methodology and models employed, to characterize cutting-edge research directions and to present implications for project planners and policymakers. The paper combines a state-of-the-art procedure for literature review, the strengths of existing reviews in the field and an exhaustive data sample. The work provides a cogent summary of the literature reviewed and

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Abbreviations: B & S, Black and Scholes model; CCGT, Combined cycle gas turbine; CCS, Carbon capture and storage; DCF, Discounted cash flows; DP, Dynamic programming; FIT, Feed-in tariff; GBM, Geometric Brownian motion; EIA, Energy Information Administration; IEEE, Institute of Electrical and Electronics Engineers; MRP, Mean reverting process; NPV, Net present value; NRE, Non-renewable energy; O & M, Operation and maintenance; PDE, Partial differential equations; RD^3, Research, development, demonstration and deployment; RE, Renewable energy; REN21, Renewable Energy Policy Network for the 21st Century; RO, Real option

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results in a number of insights that may be of value in design of RO valuation of RE and of benefit to researchers and the interested public.

The paper is structured as follows. A brief description of the theoretical background follows this introduction part, after which the methodology of the study is described. The presentation and discussion of the results is divided into three subsections covering the topics of research focus and research trends, research design, and use of RO to enable operational flexibility in RE power generation projects. The paper ends by summarizing the key findings. An appendix is included that gives a tabulated summary of the key characteristics of the papers reviewed.

2. Theoretical background

Real options theory acknowledges managerial flexibility to adjust investment projects in the light of a future uncertain and changing environment. This flexibility refers to finding and incorporating real options into investment projects, or in other words, possible managerial actions that can reshape a project to adapt to changing conditions to maintain or enhance its profitability. By analogy with financial options, RO is a right but not an obligation. Hence, an investment project with RO is more valuable than one without, because it includes a capability of change to account for changing factors in order to maximize gains.

Traditional literature differentiates the following types of real options [7]:

1. *The option to defer* investment in order to get more information or to await technological development. This option is synonymous with an option to delay or postpone, or in broader sense, a timing option.
2. *The option to stage* investment to minimize risks. This option refers to breaking down the investment phase into several stages, thus enabling termination of later stages in the case of unfavorable circumstances.
3. *The option to abandon*. This option implies an option to stop or sell the project.
4. *The option to change scale*. This option allows managers to scale back or expand the project.
5. *The option to stop/restart* operations. This option provides flexibility to adapt to changing demand or other conditions.
6. *The option to grow*. This option enables managers to gain more if market conditions or other factors are more favorable than expected.
7. *The option to change inputs/outputs*. This option refers to an ability to change input materials or fuels or output products. A common example is flex-fuel vehicles.

Nowadays, the whole investment project is often treated as one real option [8–11], in which case it is usually termed an option to invest or, analogous to financial options, a call option.

A considerable body of literature is devoted to approaches to modeling and valuing real options, including reputable textbooks [7,12] as well as concise overviews in recent review papers [3,4,6,13]. Therefore, this paper does not present general discussion of development of the methodology from financial to real option valuation, instead, attention is drawn to commonly used techniques found in the reviewed literature. Here five main approaches are identified:

1. *Partial differential equations (PDE)*. Initially used for valuing financial options, the Black-Scholes formula [14] has been adopted for RO valuation. PDE, in general, are applied to formulate specific assumptions or different types of RO [12].
2. *Binomial trees* (or lattices) were initially presented by Cox et al. [15] as a binomial options pricing model. The approach represents a discrete-time model of asset price evolution with two (or more in advanced methods) alternative future outcomes in each step.
3. *Simulation*, in particular Monte Carlo simulation, creates a distribution of project values taking into account all given sources of uncertainty [16]. Monte Carlo simulation could be considered as the easiest way to value RO of complex projects, since it does not require formulation of cash flow through differential equations or trees. However, it appears to be the most computationally expensive approach.
4. *Fuzzy sets based approaches*. In recent years, some modern techniques to value real options have exploited fuzzy set theory, e.g. the pay-off method [17]. Modeling value distribution as fuzzy numbers allows advantages of simulation-based methods to be retained while reducing computational requirements. These methods have, however, not been widely adopted.
5. *Dynamic programming*. In addition to the above listed methods, some researchers use recursive optimization methods such as dynamic programming (DP) [18–20]. The approach allows the optimal timing of the investment to be found and enables different types of RO to be combined with various possible scenarios. The underlying idea behind the method is to compare the value of different investment realization scenarios with a so-called continuation value (the value of waiting and realizing the optimal scenario in future periods) moving backwards from the last period to the initial one. In each step, the value of the scenario is evaluated using one of the above-mentioned methods, e.g. PDE or simulation. As a result, the optimal solution and timing for the investment in an uncertain environment can be defined.

Since flexibility is only valuable in the presence of an uncertain environment, an important part of RO valuation is definition of the sources of uncertainty and modeling of their possible development. Again, a variety of methods can be applied. However, researchers most often utilize stochastic modeling, including geometric Brownian motion (GBM), mean reverting processes (MRP) or binomial trees that are discreet-time approximations of GBM. Some specific types of uncertainty require specific models, for example, uncertainty in technology cost and efficiency is usually modeled with learning curves. The interested reader is encouraged to visit [21] for a study on the fit of the aforementioned types of valuation models with different types of uncertainty.

As can be seen from the discussion above, many different types of RO exist and there are many different approaches to RO valuation, which explains the significant research design variability in the literature.

3. Methodology

This literature review follows the state-of-the-art practice proposed by the Webster and Watson [22] as well as incorporating the strengths of previously-published literature reviews in the field [3,4]. The reviewed papers are analyzed using several parameters, and the results are then presented in a quantitative form.

A three-part paper selection process was used to gather the relevant literature (Fig. 1).

The initial search in the SCOPUS database was limited by the following criteria:

1. A real option approach is used;
2. At least one type of renewable energy technology is evaluated;
3. The language of the article is English.

The following combination of key words was used as a search criterion: “renewable energy” and “real option”. With the language

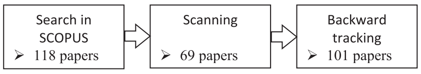

Fig. 1. Literature selection process.

limitation, the query returned one hundred eighteen results. Forty-nine papers were excluded based on abstract scanning, resulting in sixty-nine candidates for the review. The backward tracking included analysis of references from the selected papers and thematic reviews, a separate search in the proceedings of the major conference in the field, International Conference on Real Options, and a repeat of the same search in the Web of Science database. In total, one hundred and one papers were selected for further study.

The review omits studies that apply RO valuation in the presence of renewable energy but not for its evaluation, see e.g [23–27]. In addition, smart-grid related studies are excluded; readers are referred to an existing review on RO valuation of smart-grids [28].

Following the best practices of existing reviews in the field [3,4] and expanding them, the selected papers were screened for the following features:

4. Year of publication.
5. Country – the country for which the research is conducted.
6. Focus – the research focus, i.e. project valuation, supporting policy assessment or R & D.
7. Technology type – the kind of renewable energy technology evaluated.
8. Uncertainty sources – the sources of uncertainty that are taken into consideration.
9. Uncertainty modeling – the stochastic process chosen for uncertainty modeling.
10. Real option type – the kind of real options identified in the project.
11. Valuation approach – the approach used for real option valuation.

Detailed results of this analysis are presented in tabular form in Appendix 1.

The reliability of the research was assured by only considering academic articles from indexed scientific journals and conference materials. Research validity was achieved by strict adherence to the above criteria.

The next section summarizes and discusses the key results obtained.

4. Real option valuation in renewable energy

With growing interest in recent years in the economics of renewable energy [29], several reviews of academic papers addressing renewable energy appraisal have been published. Therefore, before considering the results of the current research, a brief critical summary of these works is presented and their observations discussed.

One of the earliest reviews of renewable energy valuation, conducted by Angeliki Menegaki in 2008 [30], covers a broad scope of cost-benefit analysis techniques. The research focused on the ability of different approaches to capture the non-monetary environmental value delivered by renewable energy projects. With respect to real option valuation, the review treats only three papers that used the approach, from a sample size of 35 articles. The conclusions outline the attractiveness of RO for policymakers, but warn about the complexity of the method for general public understanding.

Later, in 2011, Fernandez et al. [3] performed a more extensive review of the use of the RO approach in the energy sector. The research provides a historical perspective of valuation approaches, highlighting the advantages of RO theory for energy investment appraisal. Emphasizing the growing prevalence of renewable energy technologies and the uncertainty associated with RE investments, the review incorporated analysis of eleven selected studies that applied RO valuation to renewable energy projects. One of the contributions of this paper is a classification of renewable energy valuation literature into three types: project appraisal, policy assessment, and R & D valuation. These classes affect the real option types identified and methodology applied, making such differentiation valuable for analysis and generalization of the applicability of RO theory to renewable energy investments. In addition, it is the only review so far to note and highlight the use of DP in addition to other more conventional valuation methods.

Recent reviews present more narrowly-focused studies emphasizing and discussing a particular aspect of real option valuation. In this vein, Chen-Yu Chang [5] draws attention to the importance of incorporating behavioral uncertainty and the limit of risk transfer into the valuation. This claim is supported by reference to published work, although the number of papers is rather limited, less than a dozen in total. The author proposes a new framework for RE investment modeling. Martinez Cesena et al. [4] conduct a broader review (but still of less than two dozen RE papers) that accentuates the relevance of the field but notes the scarcity of research addressing real options embedded into the design of RE projects. RO in project design encompasses flexibility in technical and technological characteristics and, thus, is specific to the particular project. The complexity inherent in distinguishing such real options and the necessity to involve technical engineers in the RO analysis are the main reasons given for the lack of such research. In the design of their review, Martinez Cesena et al. supplement screening of the sample papers with parameters such as the real option type identified and the uncertainty source addressed by the valuation. Including these features into the literature analysis in addition to the focus on RO in project design provides greater insight into the topic for both researchers and project developers, and is therefore adapted for the current review.

Case studies are often supported with a modest literature review. In this respect, Kim et al. [6] inspect twenty-two studies on RO in RE, classifying papers by year, country, technology type, and uncertainty sources. Less attention is drawn to the methodology employed or RO identified. Nevertheless, this work purports to present a framework analysis for developing countries highlighting such intrinsic risks as changeable policies and volatile market conditions, including loan rates, inflation and exchange rates.

More recently, a bibliographic analysis on the research trends in low-carbon energy technology investment has been presented by Yu et al. [31]. Although real option analysis is not a primary focus of the review, the authors claim that RO theory is the most comprehensive and the most suitable tool for investment appraisal of low-carbon energy projects. The work delivers observations on general topic trends, as well as authors, institutions and journals involved, familiarizing research newcomers with key works in this academic field.

As can be noticed, existing reviews, although providing valuable insights into the topic, give only a fragmentary picture of real option valuation approaches in renewable energy assessment and their scope is limited to a modest number of studies that focus on particular aspects of valuation design. To advance study in the field, the current review attempts to build on the strengths of these predecessors, expand the sample size, and present the results numerically in order to develop a more comprehensive picture of the topic and equip researchers, project developers and policymakers with a solid basis for RE investment planning and assessment.

4.1. Research focus and trends

4.1.1. Trend and country focus

The growing body of research devoted to real option valuation of renewable energy investment is illustrated in Fig. 2. The whole sample of 101 papers is distributed along a timescale based on the publication year. Overall, the figure reveals a strong positive trend with more than ten papers per annum in recent years. The current review covers only the first months of 2017, which is the cause of the low number of papers in 2017.

When the data is divided into papers having developed and emerging economies as a research focus, it can be noted that since 2008 increasing attention has been given to RE valuation in developing

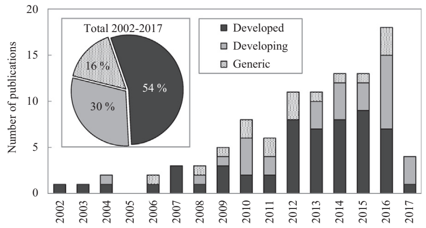

Fig. 2. Research trend and country focus.

countries. This research trend reflects real-world dynamics, where implementation of renewable energy policy has become a driving force not only for industry investments, but for academic research as well. For instance, a Renewable Energy Law was introduced in Turkey in 2005 and the first paper on RO and Turkish renewable energy was published in 2008 [32]. In Brazil, the mandatory portion of ethanol in fuel, in operation since 1976, has increased, the latest amendment was in 2007, and a study of ethanol production assessment was published in 2009 [33], and work on valuing flex-fuel cars in 2010 [34]. A paper by Yang et al. [35], published in 2010, investigates promulgation effects of the Chinese Renewable Energy Law in 2006.

The number and scope of national and regional RE support policies is increasing [2], and thus even more research devoted to RO in RE can be expected in the future. Research focusing on developing countries is likely to continue the strong positive trend of the last decade, particularly in view of the substantial RE investments being made in the developing world [1]. It should, however, be noted that although developing countries have become an attractive focus for RO research, in absolute number of papers published, attention to developed economies prevails (Fig. 2). Nevertheless, publications with a developing country as a case study already account for thirty publications in total and cover countries such as China, Brazil, Taiwan, Russia, Turkey, Liberia, Mongolia, Indonesia, and Egypt.

In total, only thirteen developed and nine developing countries are represented in the sample. By the end of 2015, renewable energy support policies were identified in 146 countries [2], which reveals the considerable potential for further research in the field.

4.1.2. Research focus and technology

The key application area of the real option approach is investment project valuation, and the greatest part of the research utilizes RO for project (62%) and R & D (6%) appraisal (Fig. 3, left). In the remaining cases, the RO approach is used as a method for analyzing the effects of policy support for RE investment. As the main aim of RE policy is to trigger investment, appraisal of investments under such policy can provide insights into policy efficiency and enables comparison of different support mechanisms.

For example, Kim and Lee [36] compare different feed-in-tariffs (FIT) and make proposals for their optimization. The authors conclude that there is no optimal policy design, rather policy design depends on the policy objectives and the tradeoff between policy efficiency in RE project promotion and its cost-effectiveness with respect to the burden on taxpayers. Furthermore, the authors note a general tendency that the higher the volatility of electricity prices on the market, the more successful FIT programs become in terms of attracting new investments.

Scatasta and Mennel [11] compare FIT and Renewable Obligation Certificates and study their effect on propensity to innovate. Their results demonstrate that neglecting risk-aversion, the certificate trading scheme favors investment in renewing RE power generation plant to a greater extent than FIT. Their explanation suggests that the higher uncertainty and risks under certificate trading also create more opportunities. Similarly, Boomsma et al. [37] explore investors' behavior under FIT and RE certificate trading and study the effects of market and policy risks under different schemes [38]. This research highlights that the certainty provided by FIT encourages earlier investment, whereas uncertain revenues under the certificate trading scheme, while tending to delay investment, give greater incentives to larger projects once a positive investment decision has been taken. Nevertheless, the authors underline their finding that the difference in market risks between these schemes is less than has previously been assumed. Finally, their model demonstrates an adverse slowing down effect of retroactive policy changes. Similar conclusions of the negative impact of policy uncertainty on RE investments has been reached in other works as well [39–41].

Yu et al. [42] compare a previous Spanish scheme with a new switchable tariff, investigate the impact of the latter on RE investments and define optimal switching strategies. Running a RO valuation model for different policy design, they find that a switchable tariff approach balances the policy efficiency inherent to fixed FIT and the cost-effectiveness commonly induced by market-based RE support mechanisms. The authors argue that the flexibility embedded in switchable tariffs allows risk reduction and provide adequate support to compensate for risks involved in investment in RE projects. The issue of integrating flexibility into RE policy design is elaborated further in section 4.3 of this paper. Research focused on RE policy assessment can provide impulses not only for improving existing policies, but also for designing support mechanisms for emerging policies.

In terms of the focus on technology type (Fig. 3, right), most researchers investigate wind power generation projects, followed by solar and small hydro. A few studies depart from these already common RE technologies and consider project valuation of non-mainstream RE technology, e.g., tidal power [43], or unorthodox energy generation such as the 'Powership' concept [44]. Less than a fifth of the reviewed papers focus on bioenergy projects, including biofuel production and flex-fuel cars.

4.2. Research design

In spite of the variety of RO analysis approaches, design of real

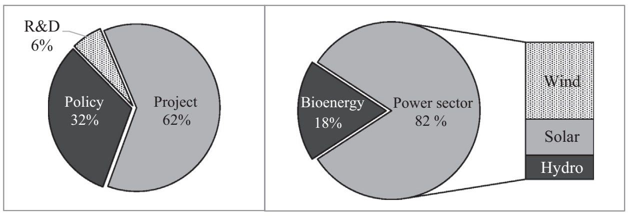

Fig. 3. Valuation focus (left) and technology type assessed (right).

Table 1
Uncertainty sources in renewable energy valuation.

Uncertainty	Number of publications	Share of sample
Electricity price	48	48 %
Technology	23	23 %
Production	21	21 %
Fuel price	18	18 %
Project value	14	15 %
CO2 price	14	14 %
Subsidy payments	12	12 %
Biomass price	9	9 %
NRE cost	9	9 %
Biofuel price	6	6 %
Demand	5	5 %
Inflation	5	5 %
Regulation	4	4 %
Exchange rate	2	2 %
O&M costs	2	2 %
Cost of capital	1	1 %

option valuation contains several common attributes: (i) identification of the sources of uncertainty, (ii) recognition of the available real options, (iii) modeling of the development of uncertain variables, and (iv) valuation of the real options. This review examines all these components of RO valuation and presents the results, first with respect to the uncertainty source and its modeling, second as regards the RO type, and finally the valuation technique used.

4.2.1. Uncertainty sources and modeling

Table 1 summarizes the sources of uncertainty identified in the different papers. The percentage values indicate the share of studies out of the whole sample that identify a particular source of uncertainty; the values do not sum up to 100% because many papers study multiple sources.

Almost half of the studied papers incorporate electricity price uncertainty into the valuation design, and this issue is clearly crucial for the power generation sector. Several other sources of uncertainty are often identified along with electricity price uncertainty, for example: technological uncertainty or, in other words, the assumption that future initial costs are expected to drop (or efficiency to rise) for immature but actively developing technologies; production uncertainty, which appertains to the variability in electricity output of renewable energy sources; and CO_2 price uncertainty, if the environmental benefits of RE projects in terms of CO_2 reduction and associated economic activity are considered. For bioenergy projects, obvious sources of uncertainty are fuel prices and biomass prices. Sometimes the whole project value is considered as an uncertainty, for example, when the Black-Scholes model is used for RO valuation, as in [9,10,45,46]. Studies that investigate switching from conventional energy to RE, especially those focusing on R & D valuation, consider the cost of non-renewable energy (NRE) technology as a source of uncertainty. Market-related uncertainty sources other than electricity prices, e.g., demand, inflation and exchange rates, are examined less often. Regulation uncertainty signifies an expectation of retroactive changes in RE policy. In the literature reviewed, 40% of studies focus on a single uncertainty source in their valuation model, most commonly electricity prices or project value. A maximum of five and an average of two sources of uncertainty are identified in the individual studies.

With respect to uncertainty modeling, most researchers opt for stochastic processes such as geometric Brownian motion or mean reversion. Ongoing debate regarding which process better reflects commodity price evolution has motivated some researchers to implement both models and compare the results. The roots of this debate lie in the origins of RO theory. Use of GBM in RO analysis has been inherited from financial option theory, where it is commonly used to address stock price evolution [47]; commodity prices, including electricity and fuel, have however been shown to have a mean reverting nature [48]. Nevertheless, Pindyck [49] argues that using GBM instead of MRP should not jeopardize the results, if the mean reversion coefficient is low.

Opinions diverge among the reviewed papers. Jang et al. [50] state that resorting to GBM may lead to overestimation of option value due to greater long-term uncertainty in comparison with mean reversion. Similarly, Brandao et al. [51] conclude that MRP provides better approximation of the actual data. However, for instance, Bastian-Pinto et al. [34] report relative independence of the results from the type of process chosen. Nevertheless, the majority of reviewed papers exploit GBM for uncertainty modeling (58%), whereas MRP is a much less popular choice (15%).

Stochastic processes are not applicable for all sources of uncertainty. Thus, for example, technological uncertainty is usually modeled with learning curves as in [52–54]. Once an appropriate model has been chosen, its parameters must be estimated, which is usually done based on historical data.

Table 2
Real option types in renewable energy valuation.

RO type	Project stage	Number of publications	Share of sample
timing	plan	61	60 %
to invest	plan	22	23 %
to abandon	op	18	18 %
technology choice	plan	9	9 %
to deploy	op	6	6 %
to switch inputs/outputs	op	6	6 %
to continue	op	5	5 %
to expand	op	4	4 %
capacity choice	plan	4	4 %
regulatory	op	4	4 %
to grow	op	3	3 %
to stop	op	3	3 %
to stage	plan	2	2 %
to stop/restart	op	2	2 %
to switch regimes	op	1	1 %
demand response	op	1	1 %

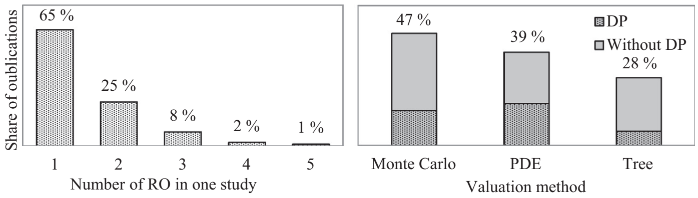

Fig. 4. Number of RO identified (left) and their valuation methods (right).

4.2.2. *Real option types and valuation techniques*

Moving to the remaining attributes of the RO approach, Table 2 illustrates RO types identified in the reviewed papers. It is a common practice to distinguish RO at different stages of an investment project. However, as opposed to complex projects such as those, e.g., in the mining industry, where one can identify RO at four different stages, namely exploration, development, extraction and reclamation [55], RE projects are known to possess limited flexibility. Cesena et al. [4] identify only two stages of RE investment where flexibility can be found: the planning stage, when the investment has not yet been undertaken, and the operational stage, when the project is already built. Fig. 4 shows the number of RO identified within one case and the valuation techniques used in the reviewed papers.

As can be seen from Table 2, the majority of RE valuation studies identify generic RO at the planning stage of a project. The most commonly identified real option is the option to defer an investment or the timing option. In many cases, in the face of various uncertainties, it is often reasonable to wait until some of this uncertainty has been resolved. The option to defer is modeled by techniques that enable comparison of different timing alternatives, in most cases either by use of binomial trees [56,57] or by incorporating DP on top of simulation models [40,52,58,59] or models formulated by PDE [38,60–64]. In 20% of the reviewed papers, timing RO is a single identified option. In addition to the question of timing, the combination of DP with other methods is also used to incorporate options in technology choice [32,65,66] or capacity choice [67,68] into optimal design of the investment.

The second most common option examined, the option to invest, reflects the notion of the whole investment project as a real option. In the majority of cases, it is modeled as a single option. Identification of this option usually coexists with valuation by the Black-Scholes formula [9,10,45,46,69], which constitutes a part of PDE without DP in Fig. 4.

Real options to abandon, deploy and continue reside in assessment studies of R & D projects or programs and are generally addressed with binomial, scenario or decision trees as the most convenient methodology to model different scenarios of R & D development [44,50,70–72]. Decision tree approaches intrinsically allow modeling of this combination of options as a compound RO.

The option to switch inputs or outputs is peculiar to bioenergy projects whose operations can be tuned to changing prices of fuels, raw materials or output products. Studies of such facilities often utilize Monte Carlo simulation [33,34,51,73,74].

An emerging trend is incorporation of fuzzy set theory into RO valuation, which allows not only uncertainty to be captured, but imprecision as well. Sheen [75] merges the Black-Scholes method with fuzzy formulated inputs, and Kozlova et al. [76] demonstrate the use of a standalone fuzzy pay-off method for RO valuation of a RE project.

From the above discussion, it can be seen that the choice of valuation approach is linked to the types of real option identified. However, the latter is often dictated by the study domain and research purpose.

Considering RO research design from a broader perspective, we would like to draw attention to the rare attempts to support RO valuation with empirical evidence. Heggedal et al. [77], for instance, perform regression analysis on construction license data and show that investors owning a portfolio of licenses act in accordance with RO theory, while the behavior of single plant owner reflects investment rules dictated by traditional NPV analysis. More evidence confirming investors' behavior in accordance with RO theory is provided from the same dataset in later works [78,79]. Another example, Bartolini and Viaggi [80], assesses RO valuation results by conducting a survey on intentions to adopt bioenergy technologies in the farming sector.

4.3. Operational flexibility in RE power generation projects

Renewable energy investments, which are characterized by long life span and high upfront capital costs, are exposed to market, political and project-internal risks during their operational stage. While bioenergy projects benefit from the operational real option to switch inputs/outputs and R & D projects possess a compound RO with respect to whether to continue, abandon or deploy the project, most RE power generation investments have limited operational flexibility and basically appear to be sunk costs as soon as an investment decision has been made. The commonly examined RO of RE generation project, the timing RO and the RO to invest are generic, and are only available at the planning stage, and thus, they do not contribute to operational flexibility. Nevertheless, operational flexibility is of crucial importance for such RE investments, as it makes the project able to respond to changing conditions. One way to incorporate operational flexibility is by creating customized real options in the project design. However, as noted in [4], developing RO in project design requires adequate technological knowledge of the project together with understanding of RO theory, which is a rarely found skillset among either project managers or engineers. The shortage of operational RO in RE power generation projects draws attention to the need for consideration of insurance and other hedging instruments. Additionally, it may be possible to enable operational flexibility by RE support policy design.

4.3.1. Real options in project design

Electricity output of run-of-river hydropower plants depends entirely on the water flow conditions. Cesena et al. [67] propose combining this technology with hydro storage facilities. Design parameters of the power plant, including location, generation capacity and storage capacity, are optimized together with investment timing in response to forecasted development of market electricity prices. Inclusion of storage allows control of electricity production volumes and, hence, flexibility in the sale of electricity to the market. The authors demonstrate that such RO design of the project increases expected profits.

Combining pumped storage with a wind farm is examined by Reuter et al. [65]. By the same logic, the storage facility enables electricity to be sold at times of high prices and stored when prices are low. This flexibility increases average profit per unit of electricity produced. However, the presented computations show that this premium does not overweigh the initial costs of storage, leading the authors to conclude that such combined power plants are not profitable without public support.

Operational flexibility is generally embedded in hybrid RE power plants. A combination of RE power generation with back-up energy systems like batteries or conventional energy generation actuate the real option to switch from the RE source to alternative production or storage when the RE resource is scarce or unavailable. Such hybrid systems are often a solution for off-grid power supply [81] and may become economically attractive as a substitute for expensive diesel generation [82]. However, addressing such hybrid RE power systems with RO valuation is not presented in the reviewed literature and represents a potential research direction.

Another approach to operational flexibility is proposed in [83]. The authors shift their focus from supply side flexibility to the demand side, suggesting investment in demand response programs. Electricity consumers under such program are offered incentives to reduce or shift their electricity consumption. In turn, this measure reduces capacity requirements for the energy system and enables flexibility within the project operation phase. The results of the study show that demand response programs are beneficial for off-grid solar PV investments.

There are rare attempts in the reviewed literature to embed operational flexibility into RE power generation projects. The general idea is to combine RE power with storage or alternative generation. Flexibility can be also integrated from the demand side by introducing demand response programs. Revealing real options at the operation stage of RE power generation projects is an emerging research direction and offers opportunities for added value for long-lasting capital-intensive RE investments.

4.3.2. Insurance and hedging in RE generation projects

Taking into account the limited operational flexibility of RE generation projects, it is unsurprising that project developers consider various insurance and hedging mechanisms to secure their revenues in the presence of uncertain resource availability and volatile markets. Indeed, if it is problematic or impossible to build flexibility into a project to make it able to response to uncertainty, hedging against this uncertainty is another alternative. This question has received some limited consideration in the research.

Hedman and Sheble [69] present real option valuation of a wind energy investment to compare hedging uncertain electricity output with either pumped storage hydro facilities or the purchasing of financial call/put options. Their analysis suggests that hedging with financial options is preferable to joint operation of wind and hydro storage plant, since in the former scenario expected profits are higher and more stable.

Bruno et al. [84] analyze hedging RE project revenues against uncertain market electricity prices with forward contracts. Their work corroborates the notion that hedging reduces cash flow uncertainty and they show that coverage of future cash flows with forward contracts depends on the risk aversion level of a particular investor. The authors emphasize that the threshold risk premium of forward contracts should be evaluated on a case-by-case basis accounting for owner's risk attitude and market perception.

Zeng et al. [85] investigate an arrangement of third party financing for distributed solar power with an option to buy back solar panels by the host. The host party allows the third party to finance, install and operate solar panels on its property. The third party benefits from electricity sales and pays charges to the host in return. The host keeps the option to buy the solar panels from the third-party at a specified time in the future. Such schemes enable delayed upfront payment and a lower price. The authors calculate the optimal timing of the buyback year and claim that such arrangements can benefit both the host and the third party.

A range of risk mitigation strategies are available for renewable energy projects, such as opting to invest in various insurance and guarantee instruments [86]. However, the effects of these strategies have not received much attention in RO literature. Nevertheless, comparing and combining available real options with financial contracts and insurance instruments can bring additional value to RE projects and represents another emerging research niche.

4.3.3. Real options in policy design

In a few cases RE support policy itself provides operational flexibility to RE power generation projects. There are four papers in the literature reviewed that identify such regulatory real options.

Yu et al. [42] examine the switchable tariff scheme introduced in Spain in 2004. Under this regulation wind power generators can choose on a yearly basis whether to receive a fixed tariff or a percentage premium over the market electricity price. The authors analyze these alternatives as a single policy and compare the scheme to a combined switchable tariff policy. The results demonstrate that a single fixed tariff incentivizes higher RE deployment levels in terms of capacity installed. On the other hand, the premium as a single policy secures the cost-effectiveness of new projects, creating higher market value of the new electricity produced. The authors claim that the combined switchable tariff scheme balances these often conflicting features of RE policy. Their results demonstrate that operational flexibility provided by the switchable policy reduces risk exposure of wind generators. To further optimize this support mechanism Yu et al. propose a monthly switching tariff that would provide even higher additional value to RE investments.

The same Spanish support mechanism is studied by Iniesta et al. [87]. The authors arrive at a similar conclusion that such regulatory options increase RE project value. Moreover, they argue that these regulatory options are beneficial for policymakers, because the administration has greater control as the policy details can be adjusted in response to shifting policy targets.

In Germany, the Renewable Energy Sources Act was amended in 2012 to introduce a premium scheme on top of fixed feed-in tariffs. Based on this amendment, Barroso and Iniesta [88] identify a regulatory real option to wind generators to switch between the fixed tariff and the premium over electricity price. They treat this RO as an American put option held by the investor and show an increase in RE project value in the presence of this option. They also characterize the provision of the support as a European call option held by the policymaker. Deducting the call option value from the put option value, they obtain an overall negative figure and claim that the policy depreciates the value of RE power generation projects. A similar conclusion is reached by the same authors in analysis of offshore wind energy support in Denmark [89]. These findings are counterintuitive and contradict other research results for both Germany [65,90] and Denmark [8], as well as feed-in tariff scheme analysis for other countries [36,91,92].

Another policy mechanism studied by Kozlova et al. [93] resembles provision of an insurance scheme rather than a regulatory real option. Introduced in Russia in 2013, the RE support aims to guarantee a certain return on investment, thus shielding project cash flows from market risks, including electricity prices, interest rates, inflation, and exchange rates. The remuneration amount is adjusted annually based on changes in listed market factors, which secures the return on investment of RE projects and reduces fluctuation in expected profits. Monte Carlo simulation results indicate substantial risk reduction for RE producers.

Regulatory real options in public policy design can be a powerful tool for promoting RE investment. Limited operational flexibility in RE power generation projects can be compensated with exogenous real options provided by the policy. Thus far, the literature reviewed identifies and analyzes regulatory real options in policy design only for switchable tariffs. All studies report increased project value under such a policy and some show that the policy enables more control over policy efficiency. Clearly, further research effort is required to enable policy design that introduces further regulatory real options.

5. Conclusion

This research presents an academic literature review on use of RO approaches in renewable energy investment valuation. Apart from providing many valuable insights for investors and policymakers, the reviewed studies illustrate the relevance of the RO approach and demonstrate its superiority over traditional capital budgeting techniques, highlighting its ability to capture uncertainty and flexibility.

Overall, a strong positive historical trend in terms of number of papers published is seen. Simultaneously, the increasing policy support for renewable energy being enacted worldwide leads us expect even greater research attention to this topic in the future.

The geographical coverage of the reviewed studies illustrates the dominance of developed countries as a focus of research. However, increasing research interest in developing countries is noted. The fact that the studies cover a mere twenty countries out of 145 having policy support for RE reveals the great potential for further research in geographic terms.

Most of the reviewed articles focus on project valuation. Policy assessment studies can however provide insights that are of value to policymakers. One general conclusion common to many studies is the negative impact of policy uncertainty on RE deployment. Expectation of retroactive policy changes slows down new RE investments.

Wind power technology is the most common energy source analyzed, with almost half of the studies addressing projects involving wind power, followed by bioenergy projects, which account for a fifth of the studies. There is a notable lack of studies considering emerging RE technologies.

When considering the design of the RO approach, a connection was found between the methodology chosen and the real options identified for valuation, reflecting the domain and purposes of the research. The use of DP on top of other valuation techniques is shown to enable comprehensive analysis of compound real options. Emerging interest in the use of fuzzy-based approaches in RO valuation was also noted, as was the importance of selection of appropriate uncertainty modeling techniques.

The review draws attention to the limited operational flexibility of RE power generation projects. The most common real options recognized in analysis of such projects are the timing RO and the RO to invest, which are both found in the planning stage of the RE project and no longer available once the investment decision has been made. To address this issue, some researchers propose integrating real options in the technological design of the project, e.g., by backing up intermittent resource wind farms with hydro storage facilities, or enabling operational flexibility from the demand side, e.g. by introducing demand response programs, or resorting to financial hedging instruments. Additionally, operating flexibility can be provided by RE support policy, if it allows investors to choose between different remuneration approaches. However, only few papers analyze such a setting. Real options in project or policy design, as well as combining real options with financial hedging, is an emerging and crucially important research area that will benefit both investors and policymakers.

This review contributes to existing literature by providing a more comprehensive picture of research applying RO reasoning to RE investments and by revealing hitherto hidden aspects such as the role of research design and the value of introducing customized real options in project design or regulatory real options in policy design.

Acknowledgments

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Appendix 1. Tabulated summary of reviewed papers

#	Authors	Year	Country	Focus	Project type	Option	Valuation approach	Uncertainty	Uncertainty modeling	Reference
1	Iniesta, J.B. and Barroso, M.M.	2015	Denmark	Policy	Wind (offshore)	Regulatory	Monte Carlo	Investment cost Electricity price Inflation production	MRP with trends and jumps	[89]
2	Rohlfs, W. and Madlener, R.	2014	Germany	Project	Wind Coal Gas CCS	Timing	Monte Carlo Tree	Electricity price Fuel price CO2 price Technology	GBM	[94]
3	Adkins, R. and Paxson, D.A.	2016	–	Policy	Generic RE	Timing	PDE DP	Electricity price Production	GBM	[95]
4	Martín-Barrera, G., Zamora-Ramírez, C. and González-González, J.M.	2016	EU	R & D policy	Solar (CSP)	Timing to abandon	Tree Monte Carlo	Project value	Tree	[96]
5	Dai, C.Y., Wang, Y.X., Li, D. and Zhou, Y.L.	2015	China	Project	Wind	To invest	PDE (B & S)	Project value	Normal distribution	[46]
6	Eissa, M.A. and Tian, B.	2017	Egypt	Project	Solar	Timing	PDE (B & S) Monte Carlo Lobatto3C-Milstein (L3CM) Finite difference	Electricity price Production Subsidy payments	GBM	[97]
7	Eryilmaz, D. and Homans, F.R.	2016	US	Policy	Wind	Timing	DP	Regulation Subsidy payments	Markov process	[41]
8	Fleten, S.E., Molnár, P., Nygård, M.T. and Linnerud, K.	2016	Norway	Project	Hydro	Timing	DP PDE	Electricity price Subsidy payments	GBM	[78]
9	Fleten, S.E., Linnerud, K., Molnár, P. and Nygaard, M.T.	2016	Norway	Project	Hydro	Timing	DP PDE	Electricity price Subsidy payments	GBM	[79]
10	Gong, P. and Li, X.	2016	China	Project	Solar Wind Biomass	Timing	Tree (trinomial tree model)	CO2 price	GBM	[98]
11	Kim, K., Park, H. and Kim, H.	2016	Indonesia	Project	Hydro	Timing to abandon	Tree (binomial lattice model)	Subsidy payments Production CO2 price O & M costs	Three-point estimation (best/moderate/worst cases)	[6]
12	Kitzing, L., Juul, N., Drud, M. and Boomsma, T.K.	2017	EU (Baltic sea)	Policy	Wind (offshore)	Timing capacity choice	DP PDE	Profits	GBM	[99]
13	Mancini, M., Sala, R.,	2016	–	Project	Wind Solar	To abandon	Tree (binomial tree)	Production subsidy	GBM	[100]

	Tedesco, D. and Travaglini, A.							Payments		
14	De Mare, G., Manganelli, B. and Nesticò, A.	2013	Italy	Project	Wind	Timing To abandon To expand	Monte Carlo	Project value	GBM	[101]
15	Sisodia, G.S., Soares, I., Ferreira, P., Banerji, S. and Prasad, R.	2015	Spain	Policy	Wind	Timing To expand	Monte Carlo PDE (B & S)	Project value	Normal distribution	[102]
16	Sisodia, G.S., Soares, I. and Ferreira, P.	2016	Spain Portugal	Policy	Wind	Timing	Monte Carlo PDE (B & S)	Project value	Normal distribution	[103]
17	Zhang, M.M., Zhou, P. and Zhou, D.Q.	2016	China	Project	Solar	Timing	DP Monte Carlo (least squares)	CO2 price NRE cost Investment cost electricity price	GBM	[104]
18	Zhang, M.M., Zhou, D.Q., Zhou, P. and Liu, G.Q.	2016	China	Policy	Solar	Timing	DP Monte Carlo (least squares)	CO2 price Investment cost	GBM	[105]
19	Zhang, M.M., Zhou, D.Q., Zhou, P. and Chen, H.T.	2017	China	Policy	Solar	Timing	DP Monte Carlo (least squares)	CO2 price investment cost Electricity price	GBM	[92]
20	Kozlova, M., Collan, M. and Luukka, P.	In Press	Russia	Policy	Wind	To invest	Monte Carlo	Investment cost Production Electricity price Inflation	Uniform distribution	[93]
21	Adkins, R., Paxson, D.	2016	–	Policy	Generic RE	Timing	PDE	Electricity price Production Subsidy payments	GBM Poisson (jump) process	[95]
22	Gahrooei, M.R., Zhang, Y., Ashuri, B., Augenbroe, G.	2016	US	Project	Solar Residential	Timing to stage	Monte Carlo DP	Demand Technology Electricity price	GBM	[106]
23	Ritzenhofen, I., Spinler, S	2016	generic	Policy	Wind	Timing	tree DP	Regulation Technology Electricity price	GBM	[39]
24	Torani, K., Rausser, G., Zilberman, D.	2016	US	Project	Solar Residential	To invest	PDE DP	Electricity price Technology cost	GBM	[18]
25	Wesseh, P.K., Lin, B.	2016	China	Policy	Wind	To invest	Tree DP	NRE cost	Tree	[107]
26	Balibrea-Iniesta, J., Sánchez-Soliño, A., Lara-Galera, A.	2015	Spain	Policy	Wind	Regulatory	Monte Carlo	Electricity price Production	MRP Weibull distribution	[87]
27	Boomsma, T.K., Linnerud, K.	2015	–	Policy	Wind	Timing	PDE DP	Electricity price Subsidy payments Regulation	GBM Markov process	[38]
28	Bruno, S., Ahmed, S.,	2015	Brazil	Project	Hydro	Timing hedging with	DP	Electricity price	Markov processes	[84]

	Shapiro, A., Street, A.				Wind	forward contracts		Forward price Production	Vector Autoregressive (VAR) processes	
29	Jeon, C., Lee, J., Shin, J.	2015	Korea	Policy	Solar	To invest	Monte Carlo System dynamics PDE (B & S)	Production Electricity price interest rate Exchange rate	Uniform and normal distribution	[108]
30	Kozlova, M., Collan, M. and Luukka, P.	2015	Russia	Project	Solar	To invest	Monte Carlo Fuzzy pay-off	Electricity price Inflation Technology Production Localization	Uniform distribution	[76]
31	Li, Y., Tseng, C.-L., Hu, G.	2015	US	Project	Bioenergy	Timing	PDE DP	Fuel price Biomass price	Wiener process with drift	[61]
32	MacDougall, S. L.	2015	Canada	Project	Tidal	Timing	PDE (B & S)	Project value	Normal distribution	[43]
33	Onar, S.Ç., Kılavuz, T.N.	2015	Turkey	Project	Wind	To invest	Monte Carlo	Production Electricity price Investment cost	Weibull distribution GBM Uniform distribution	[109]
34	Schmitz, M., Madlener, R.	2015	Germany	R & D	Powership	To abandon	Tree (binomial lattice)	Investment cost Fuel price Storage cost	log-normal distribution	[44]
35	Wesseh, P.K., Lin, B.	2015	Liberia	R & D	Generic RE	To abandon To expand To deploy	Tree (binomial lattice) DP	NRE cost Technology	Tree	[70]
36	Xian, H., Colson, G., Mei, B., Wetzstein, M.E.	2015	US	Project	Bioenergy coal & wood pellets	Timing	PDE DP	Fuel price Biofuel price	GBM	[60]
37	Zeng, Y., Klabjan, D., Arinez, J.	2015	US	Project	Solar Residential	Timing	Monte Carlo DP	Subsidy payments Demand Maintenance cost	Jacobi diffusion process Normal distribution	[85]
38	Anderson, R.C., Weersink, A.	2014	US	Project	Bioenergy	Timing	PDE DP	Project value	GBM	[62]
39	Barroso, M.M., Iniesta, J.B.	2014	Germany	Project	Wind	Regulatory	Monte Carlo	Technology Production Electricity price Inflation	MRP with trends and jumps	[88]
40	De Oliveira, D.L., Brandao, L.E., Igrejas, R., Gomes, L.L.	2014	Brazil	Project	Bioenergy	To switch inputs/ outputs	Monte Carlo	Electricity price	MRP	[73]
41	Kim, K.-T., Lee, D.-J., Park, S.-J.	2014	Korea	R & D	Wind	To abandon To deploy To continue	DP Tree (decision tree)	NRE cost	GBM	[71]
42	Kokkaew, N., Sampim, T.	2014	–	Project	Bioenergy	Timing	Tree	Electricity price CO2 price Biomass price	GBM	[57]
43	Linnerud, K.,	2014	Norway	Project	Hydro	Timing	Least squares	Electricity	GBM	[110]

	Andersson, A.M., Fleten, S.-E.						Monte Carlo	price Subsidy payments	MRP	
44	Maxwell, Christian; Davison, Matt.	2014	US	Policy	Bioenergy Ethanol	To stop/ restart Timing	DP PDE Monte Carlo	Biofuel price Biomass price	GBM	[20]
45	Passos, A.C., Street, A., Fanzeres, B., Bruno, S.	2014	Brazil	Project	Wind Hydro	To invest	Least squares Monte Carlo	Electricity price	MRP	[111]
46	Santos, L., Soares, I., Mendes, C., Ferreira, P.	2014	Portugal	Project	Hydro	Timing	Tree (binomial tree)	Electricity price	GBM	[56]
47	Sheen, J.-N.	2014	–	Project	Wind	To invest	PDE (B & S) fuzzy	Project value	triangular fuzzy number	[75]
48	Siegert, G.	2014	Germany	Policy	Biogas Bioenergy	To invest To stop	PDE (B & S) Monte Carlo	Project value	normal distribution	[112]
49	Zhang, M., Zhou, D., Zhou, P.	2014	China	Policy	Solar	To continue To abandon To invest Timing	Tree (binomial lattice)	NRE cost CO2 price technology Subsidy payments	tree	[113]
50	Adkins, R., Paxson, D.	2013	–	Policy	Generic RE	Timing	PDE	Electricity price Production	GBM	[114]
51	Brandao, L. E. T., Penedo, G. M., Bastian-Pinto, C.	2013	Brazil	Project	Biodiesel Bioenergy	To switch Inputs/ outputs	PDE Monte Carlo	Biofuel price Biomass price	GBM MRP	[51]
52	Detert, N., Kotani, K.	2013	Mongolia	Project	Coal Wind Solar thermal	Timing Technology choice	Monte Carlo DP	Fuel price	GBM MRP	[115]
53	Di Corato, L., Gazheli, A., Lagerkvist, C.-J.	2013	Sweden	Project	Bioenergy	Timing	DP PDE	Project value	GBM	[63]
54	Gazheli, A., Di Corato, L.	2013	Italy	Project	Solar	Timing	PDE	Foregone profits	GBM	[116]
55	Jang, Y-S, Lee, D-J., Oh, H.-S.	2013	Korea	R & D	Generic RE	To continue To defer To deploy To abandon	Tree (binomial tree, decision tree)	NRE cost R & D success	MRP BRM	[50]
56	Lin, B., Wesseh, P. K. Jr.	2013	China	Policy	Solar	To continue To abandon to deploy	DP Tree (binomial tree)	NRE cost Technology	GBM	[91]
57	Martinez-Cesena, E. A., Azzopardi, B., Mutale, J.	2013	UK	Project	Solar Residential	Timing	Indifference curves	Technology	–	[54]
58	Monjas-Barroso, M., Balibrea-Iniesta, J.	2013	Denmark, Finland, Portugal	Policy	Wind	To invest	Monte Carlo Tree	Technology Electricity price Inflation Production	MRP	[8]
59	Rohlfs, W., Madlener, R.	2013	Germany	Project	Wind Gas	Timing	Monte Carlo Tree	Electricity price Fuel price CO2 price Technology	GBM	[90]
60	Bartolini, F., Viaggi, D.	2012	Italy	Policy	Bioenergy	Timing	DP Monte Carlo	Project value Biomass price Electricity price	GBM	[80]

61	Boomsma, T. K., Meade, N., Fleten, S.-E.	2012	Norway	Policy	Wind	Timing To grow	PDE Monte Carlo (least squares)	Labor cost Technology Electricity price Subsidy payment	GBM	[37]
62	Fuss, S., Szolgayova, J., Khabarov, N., et al.	2012	–	Project	Gas Coal Biomass CCS Bioenergy	Timing to stop /restart	DP Monte Carlo	CO2 price	GBM	[58]
63	Gonzalez, A. O., Karali, B., Wetzstein, M. E.	2012	US	Policy	Ethanol Bioenergy	Timing	DP PDE	Biofuel price Biomass price	GBM	[64]
64	Heggedal, A. M., Linnerud K., and Fleten S.-E.	2012	Norway	Project	Hydro	Timing	least squares Monte Carlo DP	Regulation Electricity price	GBM MRP	[77]
65	Kim, B., Lim, H., Kim, H., Hong, T.	2012	Korea	Policy	Solar	To invest	PDE (B & S)	Project value	Normal distribution	[9]
66	Kim, K.-K., Lee, C.-G.	2012	–	Policy	Solar	To switch regimes	Tree	Electricity price Demand Technology	Complex formulation	[36]
67	Martinez-Cesena, E.A., Mutale, J.	2012	–	Project	Wind	Timing To abandon	Tree (scenario trees and decision trees) Monte Carlo	Production	Weibull distribution	[117]
68	Min, K.J., Lou, C., Wang, C.H.	2012	US	Project	Wind	To abandon To invest	PDE	O & M costs	GBM	[118]
69	Reuter, W. H., Fuss, S., Szolgayova, J., Obersteiner, M.	2012	Germany Norway	Project	Wind Pumped storage	Timing Technology choice	DP Monte Carlo	Electricity price	Complex formulation	[65]
70	Reuter, W. H., Szolgayova, J., Fuss, S. et al.	2012	Germany	Project	Coal Wind	Timing Technology choice	DP Monte Carlo	Subsidy payment Electricity price Production Regulation	Complex formulation	[66]
71	Di Corato, L., Moretto, M.	2011	–	Project	Biogas Bioenergy	To switch inputs/ outputs	DP PDE	Biomass price	GBM	[119]
72	Lee, S.-C.	2011	Taiwan	Project	Wind	To invest	PDE (B & S)	Project value	GBM	[45]
73	Lee, S.-C., Shih, L.-H.	2011	Taiwan	Policy	Wind	To grow To abandon To contract To expand To switch	Tree (binomial tree)	NRE cost	Tree	[120]
74	Martinez-Cesena, E.A., Mutale, J.	2011	UK	Project	Solar	Design of solar system with demand response	Tree (binomial Scenario tree)	Consumer demand	Tree	[83]
75	Martinez-Cesena, E.A., Mutale, J.	2011	–	Project	Hydro	Timing Capacity choice	Tree (binomial path-dependent scenario tree) Monte Carlo	Electricity price	GBM	[67]
76	Munoz, J. I., Contreras, J., Caamaño, J., Correia, P. F.	2011	Spain	Project	Wind	Timing to invest To abandon	Tree (trinomial decision tree) Monte Carlo	Production Electricity price	Weibull distribution MRP	[121]
77	Bastian-Pinto,	2010	Brazil	Project	Bioenergy	To switch	Monte Carlo	Biofuel price	GBM	[34]

	C., Brandao, L., Alves, M. L.				Flex-fuel cars	inputs/ outputs		Fuel price	MRP	
78	Camargo Jr., A.S., Yu, A.S.O., De S. Nascimento, P.T., Marques, J.J., Morilhas, L.J.	2010	Brazil	Project	Bioenergy Flex-fuel cars	To switch inputs/ outputs	Monte Carlo	Fuel price	GBM	[74]
79	Fuss, S., Szolgayova, J.	2010	–	Project	Coal Wind	Timing Technology choice	DP Monte Carlo	Technology Fuel price	GBM	[52]
80	Lee, Shun-Chung; Shih, Li-Hsing.	2010	Taiwan	Policy	Wind	Technology choice	Tree (binomial decision tree)	Fuel price Technology	Tree	[122]
81	Siddiqui, A., Fleten, S.-E.	2010	–	Project	General numerical example	To stage Technology choice Timing	PDE DP	Electricity price Demand Technology	GBM	[123]
82	Tolis, A. I., Rentizelas, A. A., Tatsiopoulos, I. P.	2010	Greece	Project	Gas Biomass Bioenergy	Timing Technology choice	Euler–Maruyama method Monte Carlo	Electricity price Fuel price CO2 price Technology	GBM	[124]
83	Vogstad, K., Kristoffersen, T. K.	2010	Norway	Project	Wind	Timing To grow	DP Monte Carlo	Electricity price Subsidy payments Technology	GBM	[59]
84	Yang, M., Nguyen, F., De T'Serclaes, P., Buchner, B.	2010	China	Project	Wind	Risk premium	Monte Carlo	CO2 price Technology	GBM	[35]
85	Bastian-Pinto, C., Brandao, L., Hahn, W. J.	2009	Brazil	Project	Ethanol Bioenergy	To switch inputs/ outputs	Tree (binomial tree) Monte Carlo	Biofuel price Biomass price	tree MRP	[33]
86	Fuss, S., Johansson, D. J.A., Szolgayova, J., Obersteiner, M.	2009	–	Policy	Coal CCS Wind	Timing Technology choice	DP Monte Carlo	CO2 price	GBM vs jumps	[40]
87	Mendez, M., Goyanes, A., Lamothe, P.	2009	Eastern European countries	Project	Wind	To abandon Sequential call option	Monte Carlo Tree (binomial tree)	Exchange rate Production Electricity price	GBM	[125]
88	Scatasta, S., Mennel, T.	2009	Germany	Policy	Wind	To invest	DP PDE	Electricity price Cost of capital	Markov process	[11]
89	Schmit, T. M., Luo, J., Tauer, L. W.	2009	US	Project	Bioenergy Ethanol	Timing To invest	PDE	Fuel price Biomass price	GBM	[126]
90	Bockman, T., Fleten, S.-E., Juliussen, E., Langhammer, H. J., Revdal, I.	2008	Norway	Project	Hydro	Timing	PDE DP	Electricity price	GBM	[127]
91	Kumbaroglu, G., Madlener, R., Demirel, M.	2008	Turkey	Policy	CCGT Coal Nuclear Hydro Wind	Timing Technology choice	DP PDE	Electricity price Fuel price Technology	GBM	[32]
92	Sarkis, J. and	2008	–	Project	Solar	To invest	Tree	Technology	Tree	[53]

	Tamarkin, M.						(quadranomial lattice)	CO2 price		
93	Fleten, S.-E., Maribu,, K.M., Wangensteen, I.	2007	Norway	Project	Wind	Timing Capacity choice	PDE	Electricity price	GBM	[128]
94	Kjaerland, F.	2007	Norway	Project	Hydro	Timing	PDE	Electricity price	GBM	[129]
95	Siddiqui, A. S., Marnay, C., Wiser, R. H.	2007	US	R & D	Generic RE	To continue To deploy To abandon	Tree (binomial lattice) DP	NRE cost	Tree	[72]
96	Hedman, K.W., Gerald B. S.	2006	–	Project	Wind Pumped hydro	To invest	PDE (B & S) Monte Carlo	Production	GBM	[69]
97	Yu, W., Sheble, G. B., Lopes, J. A. P., Matos, M. A.	2006	Spain	Policy	Wind	To switch tariff	Monte Carlo	Production Electricity price	MRP	[42]
98	Fleten S-E; Maribu K.M.	2004	Nordic power market	Project	Wind	Timing Capacity choice	DP PDE	Electricity price	GBM	[68]
99	Wang, T., and De Neufville, R.	2004	China	Project	Hydro	Timing	Monte Carlo tree (binomial tree)	Electricity price	Tree	[130]
100	Davis, G. A., Owens, B.	2003	US	R & D	Generic RE	Timing To deploy To abandon	PDE	Electricity price Fuel price Technology	GBM	[131]
101	Venetsanos, K., Angelopoulou, P., Tsoutsos, T.	2002	Greece	Project	Wind	To invest	PDE (B & S)	Project value	Normal distribution	[10]

References

[1] Frankfurt School UNEP Collaborating Centre. Bloomberg new energy finance. Global trends in renewable energy investment 2016; 2016.
[2] REN21. Renewables 2016 global status report 2016; 2016.
[3] Fernandes B, Cunha J, Ferreira P. The use of real options approach in energy sector investments. Renew Sustain Energy Rev 2011;15:4491–7.
[4] Martínez Ceseña EA, Mutale J, Rivas-Dávalos F. Real options theory applied to electricity generation projects: a review. Renew Sustain Energy Rev 2013;19:573–81.
[5] Chang C. A critical analysis of recent advances in the techniques for the evaluation of renewable energy projects. Int J Proj Manag 2013;31:1057–67.
[6] Kim K, Park H, Kim H. Real options analysis for renewable energy investment decisions in developing countries. Renew Sustain Energy Rev 2016.
[7] Trigeorgis L. Real options: managerial flexibility and strategy in resource allocation. Cambridge, Mass: MIT press; 1996.
[8] Monjas-Barroso M, Balibrea-Iniesta J. Valuation of projects for power generation with renewable energy: a comparative study based on real regulatory options. Energy Policy 2013;55:335–52.
[9] Kim B, Lim H, Kim H, Hong T. Determining the value of governmental subsidies for the installation of clean energy systems using real options. J Constr Eng Manag 2012;138:422–30.
[10] Venetsanos K, Angelopoulou P, Tsoutsos T. Renewable energy sources project appraisal under uncertainty: the case of wind energy exploitation within a changing energy market environment. Energy Policy 2002;30:293–307.
[11] Scatasta S, Mennel T. Comparing feed-in-tariffs and renewable obligation certificates-the case of wind farming. In: Annual international conference on real options; 2009.
[12] Dixit AK, Pindyck RS. Investment under uncertainty. Princeton, New Jersey: Princeton university press; 1994.
[13] Chang C. A critical analysis of recent advances in the techniques for the evaluation of renewable energy projects. Int J Proj Manag 2013;31:1057–67.
[14] Black F, Scholes M. The pricing of options and corporate liabilities. J Political Econ 1973:637–54.
[15] Cox JC, Ross SA, Rubinstein M. Option pricing: a simplified approach. J Financ Econ 1979;7:229–63.
[16] Boyle PP. Options: a monte carlo approach. J Financ Econ 1977;4:323–38.
[17] Collan M, Fullér R, Mezei J. A fuzzy pay-off method for real option valuation. J Appl Math Decis Sci 2009:1–14.
[18] Torani K, Rausser G, Zilberman D. Innovation subsidies versus consumer subsidies: a real options analysis of solar energy. Energy Policy 2016;92:255–69.
[19] Boomsma TK, Linnerud K. Market and policy risk under different renewable electricity support schemes. Energy 2015;89:435–48.
[20] Maxwell C, Davison M. Using real option analysis to quantify ethanol policy impact on the firm's entry into and optimal operation of corn ethanol facilities. Energy Econ 2014;42:140–51.
[21] Collan M, Haahtela T, Kyläheiko K. On the usability of real option valuation model types under different types of uncertainty. Int J Bus Innov Res 2016:18–37.
[22] Webster J, Watson RT. Analyzing the past to prepare for the future: writing a. MIS Q 2002;26:13–23.
[23] Kucsera D, Rammerstorfer M. Regulation and grid expansion investment with increased penetration of renewable generation. Resour Energy Econ 2014;37:184–200.
[24] Osthues M, Rehtanz C, Blanco G, Negnevitsky M. Real options on power system planning under uncertainties and efficiency constraints. In: Proceedings power systems computers conference, PSCC; 2014.
[25] Fridgen G, Sachs T, Häfner L, König C. Toward real options analysis of is-enabled flexibility in electricity demand. In: International conference on information systems; 2014.
[26] Hach D, Spinler S. Capacity payment impact on gas-fired generation investments under rising renewable feed-in—a real options analysis. Energy Econ 2014.
[27] Gaudard L. Pumped-storage project: a short to long term investment analysis including climate change. Renew Sustain Energy Rev 2015;49:91–9.
[28] Schachter JA, Mancarella P. A critical review of real options thinking for valuing investment flexibility in smart grids and low carbon energy systems. Renew Sustain Energy Rev 2016;56:261–71.
[29] Edenhofer O, Hirth L, Knopf B, Pahle M, Schlömer S, Schmid E, et al. On the economics of renewable energy sources. Energy Econ 2013;40(Suppl 1):S12–S23.
[30] Menegaki A. Valuation for renewable energy: a comparative review. Renew Sustain Energy Rev 2008;12:2422–37.
[31] Yu H, Wei Y, Tang B, Mi Z, Pan S. Assessment on the research trend of low-carbon energy technology investment: a bibliometric analysis. Appl Energy 2016;184:960–70.
[32] Kumbaroğlu G, Madlener R, Demirel M. A real options evaluation model for the diffusion prospects of new renewable power generation technologies. Energy Econ 2008;30:1882–908.
[33] Bastian-Pinto C, Brandão L, Hahn WJ. Flexibility as a source of value in the production of alternative fuels: the ethanol case. Energy Econ 2009;31:411–22.
[34] Bastian-Pinto C, Brandão L, Alves MdL. Valuing the switching flexibility of the ethanol-gas flex fuel car. Ann Oper Res 2010;176:333–48.

[35] Yang M, Nguyen F, De T'Serclaes P, Buchner B. Wind farm investment risks under uncertain CDM benefit in China. Energy Policy 2010;38:1436–47.

[36] Kim K, Lee C. Evaluation and optimization of feed-in tariffs. Energy Policy 2012;49:192–203.

[37] Boomsma TK, Meade N, Fleten S. Renewable energy investments under different support schemes: a real options approach. Eur J Oper Res 2012;220:225–37.

[38] Boomsma TK, Linnerud K. Market and policy risk under different renewable electricity support schemes. Energy 2015;89:435–48.

[39] Ritzenhofen I, Spinler S. Optimal design of feed-in-tariffs to stimulate renewable energy investments under regulatory uncertainty – a real options analysis. Energy Econ 2016;53:76–89.

[40] Fuss S, Johansson DJA, Szolgayova J, Obersteiner M. Impact of climate policy uncertainty on the adoption of electricity generating technologies. Energy Policy 2009;37:733–43.

[41] Eryilmaz D, Homans FR. How does uncertainty in renewable energy policy affect decisions to invest in wind energy?. Electr J 2016;29:64–71.

[42] Yu W, Sheblé GB, Lopes JAP, Matos MA. Valuation of switchable tariff for wind energy. Electr Power Syst Res 2006;76:382–8.

[43] MacDougall SL. The value of delay in tidal energy development. Energy Policy 2015;87:438–46.

[44] Schmitz M, Madlener R. Economic viability of kite-based wind energy powerships with CAES or hydrogen storage. Energy Procedia 2015;75:704–15.

[45] Lee S. Using real option analysis for highly uncertain technology investments: the case of wind energy technology. Renew Sustain Energy Rev 2011;15:4443–50.

[46] Dai C, Wang Y, Li D, Zhou Y. Renewable energy investment project evaluation model based on improved real option. In: Anonymous low-carbon city and new-type urbanization, Springer; 2015, p. 43–53.

[47] Elliott RJ, Chan L, Siu TK. Option pricing and Esscher transform under regime switching. Ann Financ 2005;1:423–32.

[48] Deng S. Stochastic models of energy commodity prices and their applications: mean-reversion with jumps and spikes university of california energy institute Berkeley; 2000.

[49] Pindyck RS. The long-run evolution of energy prices. Energy J 1999:1–27.

[50] Jang Y, Lee D, Oh H. Evaluation of new and renewable energy technologies in Korea using real options. Int J Energy Res 2013;37:1645–56.

[51] Brandão LET, Penedo GM, Bastian-Pinto C. The value of switching inputs in a biodiesel production plant. Eur J Financ 2013;19:674–88.

[52] Fuss S, Szolgayová J. Fuel price and technological uncertainty in a real options model for electricity planning. Appl Energy 2010;87:2938–44.

[53] Sarkis J, Tamarkin M. Real Options Analysis for Renewable Energy Technologies in a GHG Emissions Trading Environment. In: Anonymous emissions trading, Springer; 2008, p. 103–19.

[54] Martinez-Cesena EA, Azzopardi B, Mutale J. Assessment of domestic photovoltaic systems based on real options theory. Prog Photovolt Res Appl 2013;21:250–62.

[55] Savolainen J, Collan M, Luukka P. Analyzing operational real options in metal mining investments with a system dynamic model. Eng Econ 2016, [0].

[56] Santos L, Soares I, Mendes C, Ferreira P. Real options versus traditional methods to assess. Renew Energy Proj Renew Energy 2014;68:588–94.

[57] Kokkaew N, Sampim T. Improving economic assessments of Clean Development Mechanism projects using real options. Energy Procedia 2014;52:449–58.

[58] Fuss S, Szolgayová J, Khabarov N, Obersteiner M. Renewables and climate change mitigation: irreversible energy investment under uncertainty and portfolio effects. Energy Policy 2012;40:59–68.

[59] Vogstad K, Kristoffersen TK. Investment decisions under uncertainty using stochastic dynamic programming: a case study of wind power. In: Anonymous handbook of power systems I, Springer; 2010, p. 331–41.

[60] Xian H, Colson G, Mei B, Wetzstein ME. Co-firing coal with wood pellets for U.S. electricity generation: a real options analysis. Energy Policy 2015;81:106–16.

[61] Li Y, Tseng C-, Hu G. Is now a good time for Iowa to invest in cellulosic biofuels? A real options approach considering construction lead times. Int J Prod Econ 2015;167:97–107.

[62] Anderson RC, Weersink A. A real options approach for the investment decisions of a farm-based anaerobic digester. Can J Agric Econ 2014;62:69–87.

[63] Di Corato L, Gazheli A, Lagerkvist C-. Investing in energy forestry under uncertainty. Policy Econ 2013;34:56–64.

[64] Gonzalez AO, Karali B, Wetzstein ME. A public policy aid for bioenergy investment: case study of failed plants. Energy Policy 2012;51:465–73.

[65] Reuter WH, Fuss S, Szolgayová J, Obersteiner M. Investment in wind power and pumped storage in a real options model. Renew Sustain Energy Rev 2012;16:2242–8.

[66] Reuter WH, Szolgayová J, Fuss S, Obersteiner M. Renewable energy investment: policy and market impacts. Appl Energy 2012;97:249–54.

[67] Martínez-Ceseña EA, Mutale J. Application of an advanced real options approach for renewable energy generation projects planning. Renew Sustain Energy Rev 2011;15:2087–94.

[68] Fleten S, Maribu KM. Investment timing and capacity choice for small-scale wind power under uncertainty. Lawrence Berkeley National Laboratory; 2004.

[69] Hedman KW, Sheblé GB Comparing hedging methods for wind power: using pumped storage hydro units vs. options purchasing. In: PMAPS 2006. international conference on probabilistic methods applied to power systems, 2006. IEEE; 2006, p. 1–6.

[70] Wesseh PK, Lin B. Renewable energy technologies as beacon of cleaner production: a real options valuation analysis for Liberia. J Clean Prod 2015;90:300–10.

[71] Kim K-, Lee D-, Park S-. Evaluation of R & D investments in wind power in Korea using real option. Renew Sustain Energy Rev 2014;40:335–47.

[72] Siddiqui AS, Marnay C, Wiser RH. Real options valuation of US federal renewable energy research, development, demonstration, and deployment. Energy Policy 2007;35:265–79.

[73] De Oliveira DL, Brandao LE, Igrejas R, Gomes LL. Switching outputs in a bioenergy cogeneration project: a real options approach. Renew Sustain Energy Rev 2014;36:74–82.

[74] Camargo Jr AS, Yu AS, de SN, Tromboni P, Belinetti JV, Marques JJ, et al. Option value embedded on the Brazilian flex fuel vehicles; 2010, p. 1–9.

[75] Sheen J-. Real option analysis for renewable energy investment under uncertainty. Lect Notes. Electr Eng 2014;293:283–9.

[76] Kozlova M, Collan M, Luukka P. Comparison of the Datar-Mathews method and the fuzzy pay-off method through numerical results. Adv Decis Sci 2016, [2016].

[77] Heggedal A, Linnerud K, Fleten S. Uncertain climate policy decisions and investment timing: Evidence from small hydropower plants. SSRN eLibrary 2011.

[78] Fleten S, Molnár P, Nygård MT, Linnerud K. Green certificates and investments in small hydro power plants; 2016, p. 1–6.

[79] Fleten S, Linnerud K, Molnár P, Nygaard MT. Green electricity investment timing in practice: real options or net present value?. Energy 2016;116:498–506.

[80] Bartolini F, Viaggi D. An analysis of policy scenario effects on the adoption of energy production on the farm: a case study in Emilia-Romagna (Italy). Energy Policy 2012;51:454–64.

[81] Bajpai P, Dash V. Hybrid renewable energy systems for power generation in stand-alone applications: a review. Renew Sustain Energy Rev 2012;16:2926–39.

[82] Boute A. Off-grid renewable energy in remote Arctic areas: an analysis of the Russian Far East. Renew Sustain Energy Rev 2016;59:1029–37.

[83] Martinez-Cesena EA, Mutale J. Assessment of demand response value in photovoltaic systems based on real options theory. In: IEEE PES Trondheim PowerTech: power of technology for a sustainable society, POWERTECH 2011.

[84] Bruno S, Ahmed S, Shapiro A, Street A. Risk neutral and risk averse approaches to multistage renewable investment planning under uncertainty. Eur J Oper Res 2014.

[85] Zeng Y, Klabjan D, Arinez J. Distributed solar renewable generation: option contracts with renewable energy credit uncertainty. Energy Econ 2015;48:295–305.

[86] Agrawal A. Risk mitigation strategies for renewable energy project financing. Strateg Plan Energy Environ 2012;32:9–20.

[87] Balibrea-Iniesta J, Sánchez-Soliño A, Lara-Galera A. Application of real options theory to the assessment of public incentives for onshore wind energy development in Spain. Int J Energy Econ Policy 2015;5:791–800.

[88] Barroso MM, Iniesta JB. A valuation of wind power projects in Germany using real regulatory options. Energy 2014;77:422–33.

[89] Iniesta JB, Barroso MM. Assessment of offshore wind energy projects in Denmark. A comparative study with onshore projects based on regulatory real options. J Sol Energy Eng Trans ASME 2015:137.

[90] Rohlfs W, Madlener R. Investment decisions under uncertainty: CCS competing with green energy technologies. Energy Procedia 2013;37:7029–38.

[91] Lin B, Wesseh PK. Jr, Valuing Chinese feed-in tariffs program for solar power generation: a real options analysis. Renew Sustain Energy Rev 2013;28:474–82.

[92] Zhang M, Zhou D, Zhou P, Chen H. Optimal design of subsidy to stimulate renewable energy investments: the case of China. Renew Sustain Energy Rev 2016.

[93] Kozlova M, Collan M, Luukka P. Russian mechanism to support renewable energy investments: before and after analysis. In: Computational Methods and Models for Transport – New Challenges for the Greening of Transport Systems, 45. Springer International Publishing; 2017. http://dx.doi.org/10.1007/978-3-319-54490-8 http://www.springer.com/gp/book/9783319544892.

[94] Rohlfs W, Madlener R. Optimal investment strategies in power generation assets: the role of technological choice and existing portfolios in the deployment of low-carbon technologies. Int J Greenh Gas Control 2014;28:114–25.

[95] Adkins R, Paxson D. Subsidies for renewable energy facilities under uncertainty. Manch Sch 2016;84:222–50.

[96] Martín-Barrera G, Zamora-Ramírez C, González-González JM. Application of real options valuation for analysing the impact of public R & D financing on renewable energy projects: a company′ s perspective. Renew Sustain Energy Rev 2016;63:292–301.

[97] Eissa MA, Tian B. Lobatto-Milstein numerical method in application of uncertainty investment of solar power projects. Energies 2017;10:43.

[98] Gong P, Li X. Study on the investment value and investment opportunity of renewable energies under the carbon trading system. Chin J Popul Resour Environ 2016;14:271–81.

[99] Kitzing L, Juul N, Drud M, Boomsma TK. A real options approach to analyse wind energy investments under different support schemes. Appl Energy 2017;188:83–96.

[100] Mancini M, Sala R, Tedesco D, Travaglini A. A real options investment model for the evaluation of wind and photovoltaic plants; 2016, p. 1101–5.

[101] De Mare G, Manganelli B, Nesticò A. The economic evaluation of investments in the energy sector: A model for the optimization of the scenario analyses. In: Proceedings of international conference on computational science and its applications. Springer, Berlin Heidelberg; 2013, p. 359–74.

[102] Sisodia GS, Soares I, Ferreira P, Banerji S, Prasad R. Projected business risk of regulatory change on wind power project: case of Spain. Energy Procedia 2015;79:1054–60.

[103] Sisodia GS, Soares I, Ferreira P. Modeling business risk: the effect of regulatory revision on renewable energy investment-The Iberian case. Renew Energy 2016;95:303–13.

[104] Zhang M, Zhou P, Zhou D. A real options model for renewable energy investment with application to solar photovoltaic power generation in China. Energy Econ

2016;59:213–26.
[105] Zhang M, Zhou D, Zhou P, Liu G. Optimal feed-in tariff for solar photovoltaic power generation in China: a real options analysis. Energy Policy 2016;97:181–92.
[106] Gahrooei MR, Zhang Y, Ashuri B, Augenbroe G. Timing residential photovoltaic investments in the presence of demand uncertainties. Sustain Cities Soc 2016;20:109–23.
[107] Wesseh PK, Lin B. A real options valuation of Chinese wind energy technologies for power generation: do benefits from the feed-in tariffs outweigh costs?. J Clean Prod 2016;112:1591–9.
[108] Jeon C, Lee J, Shin J. Optimal subsidy estimation method using system dynamics and the real option model: photovoltaic technology case. Appl Energy 2015;142:33–43.
[109] Onar SÇ, Kilavuz TN. Risk analysis of wind energy investments in Turkey. Hum Ecol Risk Assess 2015;21:1230–45.
[110] Linnerud K, Andersson AM, Fleten S-. Investment timing under uncertain renewable energy policy: an empirical study of small hydropower projects. Energy 2014;78:154–64.
[111] Passos AC, Street A, Fanzeres B, Bruno S. A novel framework to define the premium for investment in complementary renewable projects. In: Proceedings power systems computers conference, PSCC; 2014.
[112] Siegert G. Costs, benefits, and security of supply in bio-electricity feed-in tariff systems: a real options approach; 2014.
[113] Zhang M, Zhou D, Zhou P. A real option model for renewable energy policy evaluation with application to solar PV power generation in China. Renew Sustain Energy Rev 2014;40:944–55.
[114] Adkins R, Paxson D. Subsidies for renewable energy under uncertainty; 2013.
[115] Detert N, Kotani K. Real options approach to renewable energy investments in Mongolia. Energy Policy 2013;56:136–50.
[116] Gazheli A, Di Corato L. Land-use change and solar energy production: a real option approach. Agric Financ Rev 2013;73:507–25.
[117] Martinez-Cesena EA, Mutale J. Wind power projects planning considering real options for the wind resource assessment. IEEE Trans Sustain Energy 2012;3:158–66.
[118] Min KJ, Lou C, Wang C. An exit and entry study of renewable power producers: a real options approach. Eng Econ 2012;57:55–75.
[119] Di Corato L, Moretto M. Investing in biogas: timing, technological choice and the value of flexibility from input mix. Energy Econ 2011;33:1186–93.
[120] Lee S, Shih L. Enhancing renewable and sustainable energy development based on an options-based policy evaluation framework: case study of wind energy technology in Taiwan. Renew Sustain Energy Rev 2011;15:2185–98.
[121] Muñoz J, Contreras J, Caamaño J, Correia P. A decision-making tool for project investments based on real options: the case of wind power generation. Ann Oper Res 2011;186:465–90.
[122] Lee S, Shih L. Renewable energy policy evaluation using real option model — The case of Taiwan. Energy Econ 2010;32(Suppl 1):S67–S78.
[123] Siddiqui A, Fleten S. How to proceed with competing alternative energy technologies: a real options analysis. Energy Econ 2010;32:817–30.
[124] Tolis AI, Rentizelas AA, Tatsiopoulos IP. Time-dependent opportunities in energy business: a comparative study of locally available renewable and conventional fuels. Renew Sustain Energy Rev 2010;14:384–93.
[125] Méndez M, Goyanes A, Lamothe P. Real options valuation of a wind farm. Univ Bus Rev 2009.
[126] Schmit TM, Luo J, Tauer LW. Ethanol plant investment using net present value and real options analyses. Biomass Bioenergy 2009;33:1442–51.
[127] Bøckman T, Fleten S, Juliussen E, Langhammer HJ, Revdal I. Investment timing and optimal capacity choice for small hydropower projects. Eur J Oper Res 2008;190:255–67.
[128] Fleten S-, Maribu KM, Wangensteen I. Optimal investment strategies in decentralized renewable power generation under uncertainty. Energy 2007;32:803–15.
[129] Kjærland F. A real option analysis of investments in hydropower—the case of Norway. Energy Policy 2007;35:5901–8.
[130] Wang T, De Neufville R. Building real options into physical systems with stochastic mixed-integer programming; 2004.
[131] Davis GA, Owens B. Optimizing the level of renewable electric R & D expenditures using real options analysis. Energy Policy 2003;31:1589–608.

Publication III

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Russian Mechanism to Support Renewable Energy Investments: Before and After Analysis

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Chapter 15
Russian Mechanism to Support Renewable Energy Investments: Before and After Analysis

Mariia Kozlova, Mikael Collan and Pasi Luukka

Abstract This chapter presents an analysis of how the new Russian support policy for renewable energy investments changes the expected profitability of renewable energy investments in Russia. A comparative analysis of investment profitability in the before and after support policy cases is presented for a wind farm investment to illustrate the effect of the policy. This chapter is among the first to comparatively analyze the effect of the Russian renewable energy support mechanism on investment project profitability.

15.1 Introduction

To ensure strategic investments in emerging technologies in the energy sector such as investments in renewable energy (RE) that cannot at this time compete with conventional solutions in industrial scale and in terms of profitability, policy makers may introduce support mechanisms. Design of support mechanisms has turned out to be a crucial element in being able to incentivize the deployment of RE technologies into the energy markets. This is due to the maturity level of the present day technology—RE power projects are typically not profitable without policy support. It remains to be seen how fast the development of technology is able to change the situation. Ideally, a supporting policy for RE should serve multiple goals, such as reducing the risks of investment and providing motivation to invest cost efficiently, it should also be feasible from the point of the society that is paying for the bill. Typically, the

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main RE support policy types used include a “remuneration scheme” that guarantees an investor supplemental income to strengthen profitability, if an investment fulfills the policy given criteria. The level of the supplemental income can be defined in different ways and common ways to do this include, e.g., using a special price to be paid for electricity produced by RE investments (feed-in tariffs); exploring the minimum acceptable electricity price through competitive auctions; and letting the markets define the price by establishment of RE certificate trade, which RE producers receive for their production (Boute 2015).

In this chapter we concentrate on studying the Russian RE support mechanism for the Russian wholesale energy market. Under the present day conditions, industrial-scale renewable energy production investments in Russia are seldom considered as a relevant option without the support mechanism and would be deemed “universally” unprofitable without one. The focus of this chapter is to study the effect the Russian RE incentive mechanism has on the profitability of Russian RE investments. The analysis presented is based on the codified details of the Russian RE mechanism and its pricing instructions that available in the original Russian language legislative procedures (Russian law) (Government of Russian Federation 2013a, b, 2015), in a policy report (International Finance Corporation 2013), and a recently published by academic paper (Kozlova and Collan 2016). Likely due to the lack of English language sources on the Russian RE policy it has received relatively little attention in the academic literature.

Previous literature that studies the Russian RE policy includes a qualitative study of the draft version of policy (Boute 2012), an analysis of its impact on the Russian electricity and capacity prices (Vasileva et al. 2015), and a number of investigations concerning RE investment profitability in Russia (Kozlova and Collan 2015, 2016; Kozlova et al. 2015). In this respect the recent paper (Kozlova and Collan 2016) is the closest match to the analysis presented in this chapter and studies the effects of different factors on RE project profitability under the Russian capacity-based support and examines the policy’s interim success. The study is limited to using classical investment analysis and sensitivity analysis and in those terms offers a simplified picture. The aim of this research is to perform a comparative “before – after” study on the effect of the Russian RE policy to RE investments in Russia. To the best of our knowledge this is a first time the results of such a study are reported.

As a basis for the study, we use a previously presented (Kozlova 2015) system dynamic investment model and use simulation analysis to study the profitability of a wind farm investment in Russia with and without the supporting policy. The results show that the policy has a significant effect to project profitability, when a project fulfills the policy goals.

This chapter continues by shortly presenting the Russian support mechanism for renewable energy, then a simulation analysis of the profitability of a stylized wind farm investment case is made, ceteris paribus, with and without the supporting policy in place, and finally the paper is closed with a discussion and conclusions are drawn.

15.2 Russian Capacity Market and the Support Mechanism for RE Investments

Russian capacity mechanism for renewable energy support is an extension to the pre-existing Russian national capacity trade principles. The Russian power market consists of a capacity market that operates alongside the electricity market (Gore et al. 2012; Government of Russian Federation 2010a). The idea behind capacity trade is to assure ability of a power system to meet electricity demand in the long term by timely incentivizing investments in new power plants. Selling capacity means getting paid for being available to produce electricity (Olsina et al. 2014).

The Russian capacity market is organized through competitive capacity selection that is carried out by the centralized infrastructure organization System Operator (SO), where existing power generators submit their bids with available volumes of installed capacity for a pre-specified period (NP Market Council 2012). In addition, new planned projects compete for long-term capacity delivery agreements with regulated price (Boute 2012). Capacity power generators that have won contracts are obliged to follow dispatching orders from the SO that enable the management of the power system operation. On the demand side, each electricity buyer in the wholesale market is obliged to buy capacity according to the buyer's peak demand. The price of capacity is defined as a weighted average of contracted and auctioned capacity prices that include the "winning bids" of auctions and the regulated tariffs of long-term capacity delivery agreements (Gore and Viljainen 2014). Notably, the procedure of capacity price calculation for the long-term agreements is designed to assure a riskless return on each investment project (Government of Russian Federation 2010b). This mechanism is taken as a foundation for designing the remuneration scheme for renewable energy support. In May 2013, the Government of Russian Federation presented an extended capacity mechanism that is specific to RE power generation, with the aim to support the deployment of almost 6 GW of new renewable energy capacity by the year 2020 (Government of Russian Federation 2013a, b). Once a year, competitive capacity auctions are conducted for investment projects into wind, solar PV, and small (<25 MW) hydropower. The selection of projects is carried out for a four-years-ahead commercialization window and is based on (i) compliance to participation requirements and on (ii) the least planned capital costs criterion. There is a set yearly target installed capacity volume for each particular RE technology, up to which projects are selected. The participation requirements include a technology-specific capital expenditure limit and a requirement to procure a share of the used equipment from local Russian manufacturers (local content) (International Finance Corporation 2013).

The selected projects are eligible for a long-term capacity delivery agreement that allows them to benefit from monthly capacity payments for fifteen years, starting from these projects' commercialization date. The capacity agreement comes into force only after a qualification procedure after the construction end in accordance with (Government of Russian Federation 2008). The procedure registers a power plant as one operating on a renewable energy source and controls and confirms the fulfillment of the local content requirement. The policy obliges the winning RE projects to start operations on time and penalizes for delays, while the obligation that in place for “conventional energy production” facilities to follow dispatching orders is “softened” to the requirement of complying with SO orders to switch off electricity production (Government of Russian Federation 2013a).

The RE capacity price calculation is centralized and the procedure is designed to guarantee a specific return on investment regardless of the changing market conditions. The guaranteed return is defined as 12% annually corrected by changes in market interest rates (or 15% for projects auctioned before 1.01.2016). The market interest rates are represented by long-term Russian government bond yield. The capacity payments are designed to cover project costs and to provide some return over it. The estimated project costs comprise of capital expenditures (CapEx), operating expenses (OpEx), and of taxes. The capital expenditures are directly taken from the submitted bid information and are project-specific. They are converted into monthly payments by means of variable rate annuity. The ‘foreign’ share of the capital costs is translated to rubles during the project investment phase. For operating expenses the mechanism sets technology-specific norms that are corrected with inflation, which is incorporated into the calculation by using the consumer price index as a proxy. Project-specific property tax forecast, based on planned capital costs and a 20% income tax are included in the estimated project expenses for capacity price calculation.

The complex calculation of the capacity payments introduces a complicated “effect” that influences project profitability analysis. The key market and project-internal factors directly affect project profitability, while they also enter in the capacity price payment computations and create “cross-effects” on project profitability (see Fig. 15.1). It can be understood that the procedure is rather complex. For details we refer the interested reader to study Appendix 2 of (Kozlova and Collan 2016).

Capacity sales are not the only source of revenues for a power plant project, there is also income from the electricity sales. This is why the capacity payments do not cover all the estimated project costs, but only the share of costs that is computed via

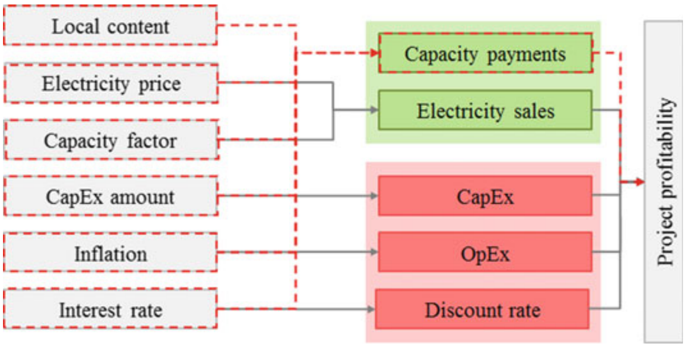

Fig. 15.1 The factors affecting Russian RE investment profitability

an analysis of an averaged project. This share of expenses is also a subject to annual recalculation, based on changing electricity prices and changes in other conditions (Government of Russian Federation 2013a, 2015).

The mechanism uses several ways to shape investor motivation to invest in RE projects, typically non-conformity with requirements decreases the support received, such cases include situations where, the plant qualification procedure reveals that the local content requirement is not fulfilled, the volume of the yearly produced electricity is too low, and orders of the System Operator to switch off the electricity production to maintain the balance in the system are not followed.

To summarize, the RE capacity price is calculated for each project on an annual basis and the aim is to provide a riskless return on the RE investment. The capacity price is adjusted based on the changing market conditions that include interest rates, electricity prices, inflation, and exchange rates. Project-specific factors such as capital costs, local content, and electricity production performance are taken into account. More detailed information about the policy and the capacity pricing can be found in (Boute 2012; International Finance Corporation 2013; Kozlova and Collan 2016) and from the original Russian legislation (Government of Russian Federation 2013a, b, 2015).

In the following section of this chapter we present a case and a numerical illustration that uncovers the effect of the Russian RE support mechanism on the profitability of a wind farm investment.

15.3 Case: Effect of the Russian RE Support Mechanism on a Wind Farm Investment Profitability

The analysis presented is based on the use of a system dynamic model built to study the profitability of a stylized wind farm investment. The model used has been presented in detail in (Kozlova 2015). The model realized with Matlab Simulink®, is built to fully represent the details of the Russian RE support mechanism, and the profitability calculation part of the model is based on using a typical discounted cash-flow logic that returns the project net present value (NPV) as a result. The model is used as the basis for a Monte Carlo simulation (Hacura et al. 2001; Kwak and Ingall 2007). The simulated NPV results are presented as histograms. We have chosen a 10 MW wind farm as the case to be studied, solar PV and small hydropower projects generate very similar results. The wind farm is assumed to be commissioned in 2017, and to start generating cash-flows immediately thereafter for the next 20 years. In the base case investment the total capital costs are assumed to be equal to cost level set by the Russian legislation limit of 110 Mrub./MW. The operating costs are assumed to be equal to the normative 188 Krub./MW per month, adjusted with inflation. We assume inflation to be an uncertain variable and assume it to stay within a range of 1 to 1.7, in terms of consumer price index. The revenues are treated as uncertain and they are modeled to consist of electricity sales with uncertain price that are assumed

Table 15.1 Summary of the parameter values and settings for the simulation runs

Run	Policy	CapEx (of the limit 110 Mrub./MW)	Capacity factor (from target 27%)	Local content	Electricity price	Consumer price index
A	*Not in place*	*Uncertain 100–150%*	*Uncertain 30–100%*	–	*Uncertain 1–3 rub./kWh*	*Uncertain 1–1.7*
B	In place	*Uncertain 100–150%*	*Uncertain 30–100%*	*Uncertain*	*Uncertain 1–3 rub./kWh*	*Uncertain 1–1.7*
C	In place	Certain 100%	High 90–100%	Fulfilled	*Uncertain 1–3 rub./kWh*	*Uncertain 1–1.7*

to range from 1 to 3 rub./kWh (corresponding to typical prices on the markets), by a capacity factor that is equal to the target, and the capacity payments that are calculated according to the support mechanism procedure. Values of the uncertain variables are expected to have a uniform distribution, except for the "local content" variable that is binary and may only take the value zero or one. The Russian risk-free rate used in all calculations is assumed to be fixed at ten percent—its effects are studied separately.

Three simulation runs are performed with the model, one without the support policy (run A), one with the support policy (run B), and a third one to illustrate the situation, where a project is able to completely fulfill the requirements of the support policy and thus being able to enjoy the full benefits of the said policy (run C). Each simulation run consisted of 100,000 simulation rounds. Details for the three simulation runs are visible in Table 15.1.

Market uncertainty represented in the model by electricity prices and inflation is modeled equally through the all three runs. The run A represents no policy situation, thus the project receives no capacity payments and benefits only from electricity sales. We assume possibility of CapEx increase to a maximum of 150% of the basic value of 110 Mrub./MW. The capacity factor used in the RE support mechanism depends on resource availability and we assume it to vary within a broad range from 30 to 100% of the target capacity factor that is equal to 27% for wind power.

The difference in run A without the supporting policy in place and run B, where the policy is in place, is the appearance of the supporting subsidy payments and the "local content" variable. The local content is typically fulfilled, as the investors most likely will not start project construction if the local content requirement cannot be fulfilled, because this would mean almost certainly that the project is unprofitable.

Run C illustrates the situation when the project is able to comply with all policy requirements and achieves the full support payments without any penalties for underperformance. Figure 15.2 presents the resulting NPV distributions from the three runs as histograms.

We can see from Fig. 15.2 how the introduction of the supporting mechanism changes the NPV distribution of the investment (Fig. 15.2a, b). What is important to notice is that the distribution resulting from the "no support mechanism" case

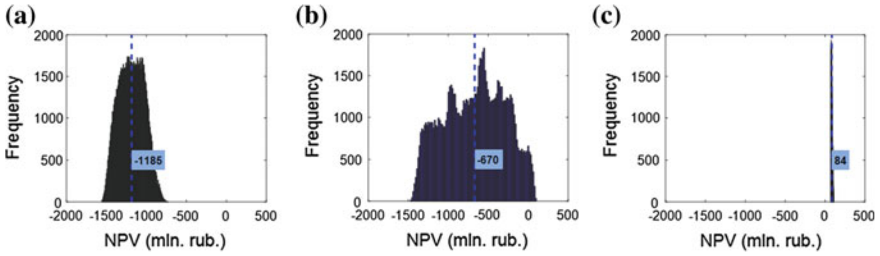

Fig. 15.2 NPV distributions for three scenarios (expected mean highlighted)

(run A) consists of only negative profitability outcomes, while the presence of the supporting mechanism shifts the distribution to the right and creates a possibility for profitable investment.

Results from run A are realistic in the sense that industrial-scale RE investments have not been profitable in Russia without support. The distribution that results from run B has a multi-peak shape that is caused by complex rules behind the support mechanism that determines the capacity remuneration paid to the investment under different circumstances. The lower bound of the distribution remains the same in both cases, because in case of poor project performance also a project "under" the support mechanism remains without any support. The difference between the two distributions can be simply calculated as the difference between the mean NPV values of runs A and B, which amounts to 515 million rubles for the investment project or more generally 52 million rubles per 1 MW of wind power installed capacity. This can also be interpreted as a real option value that is generated by the support mechanism. Comparing the means may not be very useful while both are negative, therefore we have also separately studied the situation of a project that is able to fulfill all the requirements of the support policy (run C).

The resulting distribution from run C is very concentrated and entirely in the positive area. This means that under the studied conditions a project that is able to fulfill all the set requirements of the support policy is able to guarantee positive NPV with a small variation of outcomes even in the presence of the uncertain market factors. This highlights the fact that it makes sense for the investors to be proactive in pushing their performance to fulfill the requirements of the policy. This is also in line with the policy objectives. For such projects the value of the support policy, in comparison to the preceding situation without the policy, is quite remarkable and stands at 1269 million rubles, or 127 million rubles per MW. This can be considered a real option value.

The Russian RE capacity mechanism shields investors not only from the price risk, but also from the interest rate risk. Therefore, the effects of changing interest rates on the project profitability require separate attention. The capacity price is computed as an annuity with variable rate that is adjusted to the changes in the local risk-free rate. Thus, an increase in the risk-free rate leads to higher capacity payments, and consequently to a higher internal rate of return of the project. Technically speaking,

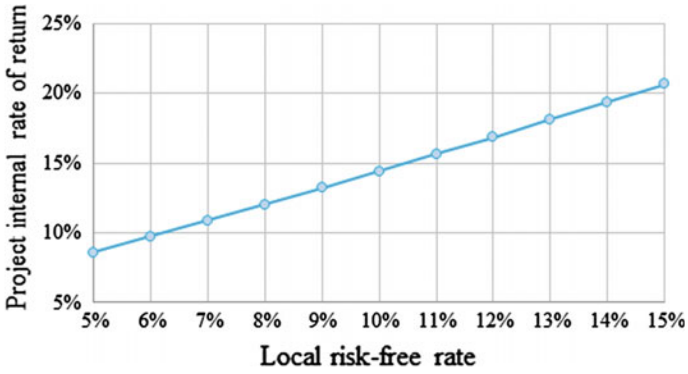

Fig. 15.3 Sensitivity of project internal rate of return (IRR) to the Russian risk-free rate under the support policy

without such mechanism in place the higher interest rates would reduce the NPV due to higher discount rates. The design of Russian RE support offsets this reduction effect by offering an increased capacity price when interest rates rise and aims to keep project profitability on the same level. This feature is designed to enable investors to cope with higher costs of financing without harming the project profitability.

A numerical sensitivity analysis performed of the effect of the Russian risk-free rate to the project profitability shows that there is a close to linear positive relationship between the project IRR and the risk-free rate arising from the remuneration design, see Fig. 15.3.

This is a non-insignificant analysis in the Russian context, where the risk-free rate may experience considerable changes over time. What is interesting and important to note is that the choice of contract in terms of floating or fixed interest on the project debt plays a role in project profitability: change in the interest rate of a floating rate loan is most likely offset by the support mechanism to a large extent.

In general, the results show that the Russian RE support mechanism is able to provide higher profitability to RE projects and projects that are able to consistently fulfill the set requirements may enjoy a situation of low risk profitability. This also means that investors should proactively try to steer their investments into meeting the set criteria.

15.4 Discussion and Conclusions

In this chapter we showed how the Russian renewable energy support mechanism works and how it changes the profitability outlook of RE power investments in Russia. The Russian RE support mechanism is unique in terms of its construct, which is rather complex. The mechanism aims to guarantee profitability for investments that fulfill the set criteria by offering capacity payments to RE investments. The capacity pricing mechanism that determines the size of the payments starts by defining the required

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return on investment and then uses it to compute a remuneration amount needed for a particular project to achieve this return. This remuneration is a subject to yearly recalculations in that take into account the changing market environment and the project performance in the long-term. As the result, the mechanism allows investors a lower risk with regards to the project profitability and allows them to enjoy a greater level of independence from Russian market conditions if they comply with set policy requirements. Real world results from the implementation of the said policy so far suggest that the support mechanism is able to provide sufficient incentive for investors for investment in solar power. Experience with wind and small hydropower shows that the selection of parameter values for the support mechanism needs more work with regards to these technologies.

We demonstrated with a system dynamic model of a wind power generation investment how the Russian RE support mechanism changes the profitability landscape of the investment—there is a significant and an important effect that allows projects that fulfill the set policy requirements to be profitable. This chapter is among the first, if not the first, to comparatively analyze the effect of the Russian support mechanism on the profitability of renewable energy investments in Russia.

Further research into this topic will include comparing the results with results from using other commonly used RE support mechanisms.

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References

Boute A (2015) Annual reporting of renewables: ten years of excellence, renewable energy policy network for the 21st century

Boute A (2012) Promoting renewable energy through capacity markets: an analysis of the Russian support scheme. Energy Policy 46:68–77

Gore O, Viljainen S (2014) Challenges of cross-border trade between two markets with different designs. In: 11th international conference on the european energy market (EEM14). IEEE

Gore O, Viljainen S, Makkonen M, Kuleshov D (2012) Russian electricity market reform: deregulation or re-regulation? Energy Policy 41:676–685

Government of Russian Federation (2008) Decree #426 on the qualification of renewable energy sources installations

Government of Russian Federation (2010a) Decree #1172 approving the wholesale market rules

Government of Russian Federation (2010b) Decree #238 on the determination of price parameters for the trade in capacity

Government of Russian Federation (2013a) Decree #449 on the mechanism of promoting the use of renewable energy in the wholesale market of electric energy and power

Government of Russian Federation (2013b) Resolution #861-R on amendments being made to resolution #1-R 8.01.2009 on the main directions for the state policy to improve the energy efficiency of the electricity sector on the basis of renewable energy sources for the period up to 2020

Government of Russian Federation (2015) Decree #1210 on the introduction of amendments to the certain legislative acts regarding the use of renewable energy sources in the wholesale electricity and capacity market

Hacura A, Jadamus-Hacura M, Kocot A (2001) Risk analysis in investment appraisal based on the Monte Carlo simulation technique. Eur Phys J B-Condens Matter Complex Syst 20(4):551–553

International Finance Corporation (2013) Russians new capacity-based renewable energy support scheme, an analysis of Decree no. 449

Kozlova M (2015) Analyzing the effects of the new renewable energy policy in Russia on investments into wind, solar and small hydro power. M.Phil. thesis, Lappeenranta University of Technology

Kozlova M, Collan M (2015) Financing renewable energy projects in Russia under new legislation

Kozlova M, Collan M (2016) Modeling the effects of the new Russian capacity mechanism on renewable energy investments. Energy Policy 95:350–360

Kozlova M, Collan M, Luukka P (2015) Renewable energy in emerging economies: shortly analyzing the russian incentive mechanisms for renewable energy investments. In: International research conference GSOM emerging markets conference-2015: business and government perspectives

Kwak YH, Ingall L (2007) Exploring Monte Carlo simulation applications for project management. Risk Manag 9(1):44–57

NP Market Council (2012) Wholesale market

Olsina F, Pringles R, Larisson C, Garcés F (2014) Reliability payments to generation capacity in electricity markets. Energy Policy 73:211–224

Vasileva E, Viljainen S, Sulamaa P, Kuleshov D (2015) RES support in Russia: impact on capacity and electricity market prices. Renew Energy 76:82–90

Publication IV

Kozlova M., Collan M., and Luukka P

Renewable Energy in Emerging Economies: Shortly Analyzing the Russian Incentive Mechanisms for Renewable Energy Investments

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Renewable Energy in Emerging Economies: Shortly Analyzing the Russian Incentive Mechanisms for Renewable Energy Investments

Renewable energy has become an actively developing sector in many emerging economies and there are various incentive mechanisms. Russia has implemented a unique incentive policy for renewable energy investments, based on two separate mechanisms that reduce the risks of investments into renewable energy generation.

This study presents a short analysis of the two Russian RE incentive mechanisms, illustrates the profitability effect of the capacity mechanism for investments into renewable energy on the wholesale energy market, and analyzes shortly the results from two past capacity auctions to shed light on how well the renewable energy incentive mechanism is functioning in reality.

Key words: *capacity mechanism, emerging economy, Russian renewable energy policy, renewable energy tariffs for retail markets.*

1. Introduction

Attracting investments and developing new sectors of business and industry are among the important goals of many emerging countries. The renewable energy (RE) sector represents a relatively young part of the energy industry that is still actively evolving. Developed countries that are playing the first mover role in RE investment mobilization, have experienced decaying investment volumes already for some years, meanwhile emerging economies demonstrate strong upward trend in new investments in renewable energy of $131 billion in 2014 and reaching the almost same level as investments in developed countries (Figure 1).

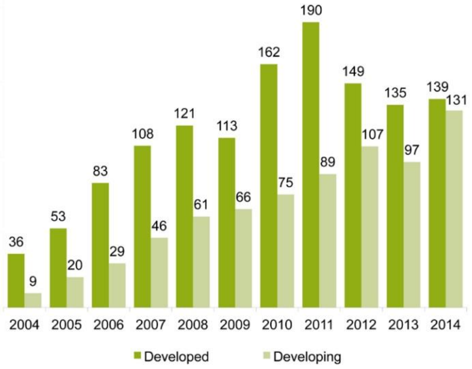

Figure 1. Global new investment in renewable energy, $bn (Frankfurt School UNEP Collaborating Centre & Bloomberg New Energy Finance, 2015).

Largest emerging economies in terms of RE investment volumes are China, Brazil, India, and South Africa. Apart from them, also several other emerging economies attracted total investment over $1 billion in 2014. These include Mexico, Indonesia, Turkey, Chile, and Kenya and yet more reached over the $500 million investment volume (Frankfurt School UNEP Collaborating Centre & Bloomberg New Energy Finance, 2015).

To provide a favorable investment environment for investments into renewable energy, governments commonly resort to investment supporting policies. In fact, the number of emerging countries that have adopted incentive policies to support investment into RE has been growing, see Figure 2.

The types of support mechanisms to incentivize RE investments vary. The most popular supporting policy type is the use of feed-in tariffs (or premiums). Feed-in tariffs are widely used all over the world and systems based on feed-in tariffs are in force in such emerging economies as China, Egypt, Kenya, and Ukraine. Another widespread policy for incentivizing RE investments is the use of auctioning production rights, where the idea is based on competing companies (potential producers) bid each other down on the price of produced electricity from renewable energy sources. Auctions are common, e.g., in South and Central America. Renewable portfolio standards, or quotas, although being active in some developed countries, including the US, have not been adopted in many emerging economies (REN21, 2014). Overall, main policy instruments used seem to support renewable energy investments by providing additional revenues for the production, other incentives include, e.g., the use of tax exemptions and financing facilitation.

Recently, Russia has joined the list of emerging countries with active renewable energy supporting mechanisms. In 2013 it introduced a renewable energy incentive mechanism for the wholesale energy market that is integrated to its existing energy trading system (Government of Russian Federation, 2013a). A distinctive feature of this mechanism is that it provides remuneration in terms of capacity installed, not based on the electricity produced (further referred to as the capacity mechanism). In addition, in early 2015 Russian government enacted a renewable energy tariff scheme for retail markets (further referred to as the tariff scheme), expanding coverage of RE support in the country (Government of Russian Federation, 2015). Both mechanisms differ in many respects from the existing RE incentive mechanisms and policies worldwide.

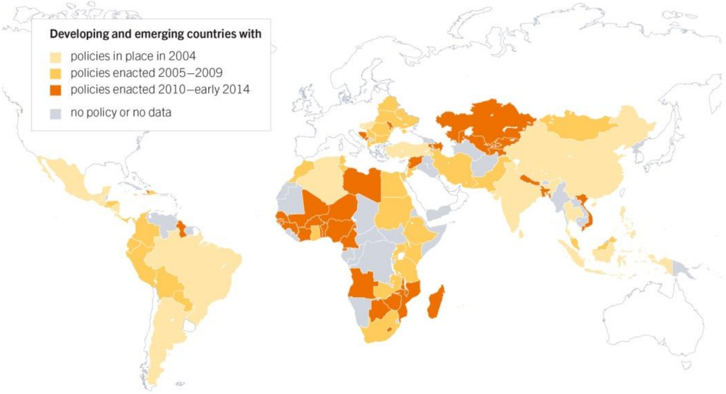

Figure 2. Developing countries with renewable energy policies (REN21, 2014).

The effects to RE investment profitability, or the success in attracting new RE investment, of these new Russian incentive schemes has not gained a lot of attention in academic literature. Current literature includes a qualitative analysis of the draft version of the Russian capacity mechanism (Boute, 2012), modeling of possible effects of the Russian capacity mechanism on energy market prices (Vasileva, Viljainen, Sulamaa, & Kuleshov, 2015), and a model-based analysis of the effects of the scheme on investors' decision-making (Kozlova, 2015). In addition, the International Finance Corporation has published reports describing the Russian renewable energy policy (2013a; 2013b). There have been no attempts so far to analyze the actual effects of the incentive systems on realized RE investment deployment. Studies on the newer Russian tariff scheme for RE retail market investments have not, to the best of our knowledge, been reported at all.

The purpose of this paper is to analyze the incentives the Russian Federation uses to promote renewable energy investment in the country, and whether these incentive systems have been successful so far. The paper combines the analysis of legislation and numerical investment case illustration on one hand, with the analysis of actual implementation results in terms of the amount of deployed RE capacity on the other. By comparing the intentional incentives with the actual realized output, this paper tries to illustrate the effectiveness of the policy.

A wind farm investment case is used to numerically illustrate the effect of the Russian capacity mechanism on the profitability of a RE project operating on the wholesale electricity production market. The tool used in the analysis is the fuzzy pay-off method for investment valuation and real option analysis (Collan, Fullér, & Mezei, 2009). Analysis of the case provides the first conclusions on the how well the new Russian RE incentive framework works, and sheds light on some important characteristics of the incentive policy, providing also insights for other emerging economies.

The paper is structured as follows: in the following section, the Russian electricity and capacity trading system are introduced supporting RE policy description starting in the subsequent section. Then we present results of investment modeling in the presence of the new capacity mechanism to analyze the effects of the policy. Further we show its actual realization results. Finally, the discussion of obtained inferences and some conclusions complete this paper.

2. Russian energy market

The Russian electricity trading system consists of a wholesale market and a retail market. Large generators sell electricity to the wholesale market, where large industrial consumers, retailers and suppliers of last resort buy it. The latter two then sell electricity to the consumers through retail markets. Smaller power generators can sell electricity directly to the retail markets, whereas medium installations, with nominal capacities between 5 and 25 MW can participate on either, the wholesale, or on the retail market. State-controlled infrastructure organizations act as market regulators. The Non-profit Partnership (NP) Market Council is a self-regulatory organization of wholesale market participants, responsible for regulation and optimization of the trading system. Its subsidiary, the Trading System Administrator (ATS) organizes the trade and conducts the settlements in the wholesale market. The System Operator (SO) is responsible for actual electricity flows and for dispatch management. A simplified structure of the Russian electricity markets is presented in Figure 3.

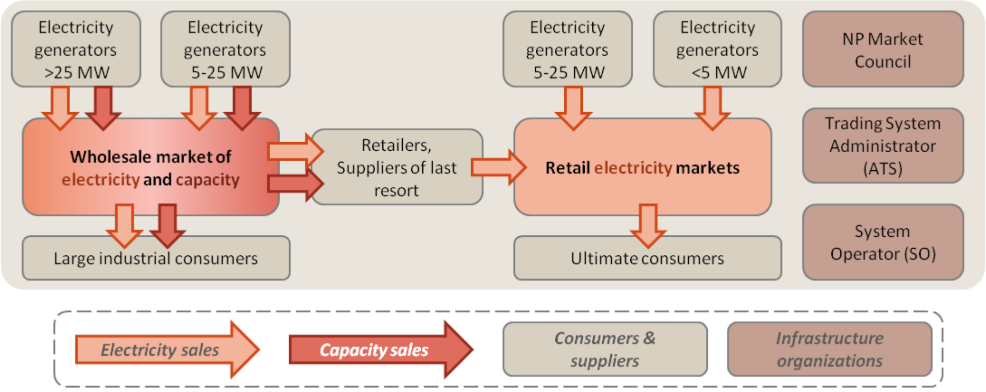

Figure 3. Simplified model of Russian electricity and capacity trading system (based on (NP Market Council, 2012a)).

A specific feature of the Russian energy trading system is that electricity is not the only commodity on the wholesale market, also capacity is traded. “Capacity is a special commodity that, when purchased, gives the wholesale market participant the right to demand that the capacity seller maintains his generating equipment in a state of availability to generate electricity of a defined quality and in the volume required to meet that participant's needs” (NP Market Council, 2012b). In the Russian system the electricity generation facilities submit their production price bids to a capacity auction, where the ATS selects bids from the lowest to the highest until the required total capacity is fulfilled. The required total capacity is defined by the System Operator (SO). It can be noted that in the Russian system some other types of capacity compensation also exist (Gore, Viljainen, Makkonen, & Kuleshov, 2012; Kuleshov, Viljainen, Annala, & Gore, 2012), these however fall outside the scope of this paper. Wholesale market actors (buyers) are obliged to buy the defined total capacity at a weighted average price, defined for different zones (Russian electricity market is distributed into zones). In addition, a separate long-term capacity market is in place for new, planned power generation investments, where new projects compete for long-term regulated capacity agreements. Capacity price within these agreements is calculated for each project in accordance with a procedure, defined by Russian legislation, and that is designed to guarantee coverage for the investment costs and a given return level.

Russian renewable energy incentive mechanism is integrated to the above-described energy trading system and is realized with long-term RE capacity contracts for the wholesale market and regulated tariffs for retail markets. The next section describes the Russian RE incentive policy in more detail.

3. Russian renewable energy policy

The legal basis for renewable energy support was introduced in the Russian legislation in 2007 (International Finance Corporation, 2011). Practical realization of the RE investment incentives started with the introduction of the RE capacity mechanism for the wholesale market in 2013. The RE energy incentive policy was extended with the introduction of the tariffs scheme for retail markets in 2015. These two incentive schemes are presented in the following two sections.

3.1 Capacity-based RE incentive mechanism for the wholesale market

The practice that exists in Russia for long-term capacity contracts for conventional energy projects was extended to wind, solar PV, and small hydro power (less than 25 MW) generation in May 2013 (Government of Russian Federation, 2013a). Since then, capacity auctions have been held annually by the ATS to select renewable energy projects that become eligible for (win) the long-term contracts. The only selection criterion is the amount of capital expenditure: the cheapest projects are accepted, until the target installed new power generation capacity for a particular year is fulfilled. The following target installed capacities are set by the Government for each year until 2020 (Table 1).

Table 1. Target RE installed capacity, MW (Government of Russian Federation, 2013b).

Technology type	2014	2015	2016	2017	2018	2019	2020	Total
Wind	100	250	250	500	750	750	1000	3600
Solar PV	120	140	200	250	270	270	270	1520
Hydro	18	26	124	124	141	159	159	751

Projects are obliged to use mostly domestically manufactured equipment and services, this is the so called “localization requirement”, and to keep capital expenditures within pre-specified limits for each year of operations. The limits are separate for the three different types of RE technology (wind, solar, and hydro).

The projects that win the RE capacity auction are entitled to a 15-year capacity contract after successful construction. In case of commercialization delay, project owners are subject to a penalty of 25% of the planned capacity payments (NP Market Council, 2006).

The RE capacity price system is designed to provide a guaranteed return on investment (ROI) of twelve percent in annual terms, corrected with the change in the national interest rate (for which the state long-term bond yield is used as a benchmark). The return calculation also includes adjustments for changes in electricity prices and the inflation. The capacity payment from the RE incentive system is dependent also on the production performance of the project, this is referred to as the “capacity factor” and is backward-looking measure of how much of a targeted, government set, energy production level has been achieved. The adjustment has three levels based on the previous year´s production: if the achieved production no more than one half of the target level the capacity payments are reduced to nothing, if the production is between 50% and 75% of the target level, 80% of the capacity price is paid, and the full capacity price is paid otherwise. Finally, if the achieved localization level (the level of “local production” in the construction of the investment) after construction is lower than required level, the capacity payments are cut down dramatically, for the whole tenure of the contract.

Summa summarum, the capacity mechanism for RE investments is designed to provide stable revenues for investors regardless of market conditions, and to motivate the investors (i) to use (local) national equipment and services, (ii) to reduce capital expenditures under competition pressure, and (iii) to actually produce electricity on the other hand.

3.2 RE incentivation through tariffs for the retail markets

To extend the coverage of the support for renewable energy the Russian Government has recently introduced a tariff scheme for RE projects operating on regional retail markets (Government of Russian Federation, 2015). The tariff scheme aims to provide a favorable investment climate for RE investments that focus on the production aimed directly at the retail market. Contrary to the capacity-based scheme for the wholesale market the tariff scheme provides remuneration in terms of the volume of electricity produced. Demand for RE is boosted by an obligation to the power distribution (grid) operators to use the electricity from renewable energy sources as a first priority, when compensating losses in the grid. Selected on a competitive basis, RE projects become a part of a regional power industry development scheme and eligible for the long-term, 15-year long, contracts with grid companies. Regional authorities are responsible for the organization of the competitions and for publishing the information about them on their official web-sites. The tariffs are designed in a similar way to the design of the capacity payments, to cover investment costs and to provide some return in excess of investment costs (14% for projects commissioned before 1.1.2017 and 12% for projects commissioned thereafter). The tariff is calculated in accordance with a federally set methodology (Federal Tariff Service, 2015). Regional deviations in tariffs may arise only from when initial capital costs are set at a lower level, or from when the planned capacity factor requirement is set higher, if so offered by a competing investment project. These changes can only push the tariffs downward. The main difference from the capacity price (per kW) system is that the tariffs are transferred to the electricity price (per kWh). This means that there is no separate need to make adjustments on the tariff, when electricity market prices change, since it is already designed to cover project costs, adjustments are however made for changes in the interest rates to keep an adequate ROI.

Some potential legal challenges were previously identified with regards to the realization of the tariff system (International Finance Corporation, 2013a), but it seems that some of them have been already overcome.

4. Case illustration

The way policy shapes profitability of investment is crucial for reaching its goals. In general, it is important to find a balance between reducing uncertainty for investors and neutralizing the burden of the costs of a support scheme for the whole energy system and the ultimate energy consumers. The Russian approach is a singular mechanism for tackling this trade-off and very different from the incentive systems used elsewhere. To illustrate how the mechanism works in reality, we present a numerical case analysis of the profitability of a medium scale on-shore wind farm project with 10 MW installed capacity with the RE capacity mechanism in place.

To investigate how the RE incentive policy shapes the uncertainty faced by an investment project, considering single number profitability indicators such as NPV will not be enough to give a complete picture of the uncertainty. For this reason we have chosen to utilize a (fuzzy) pay-off method (Collan et al., 2009) that presents the profitability of these investments as a profitability distribution that also intuitively shows the perceived downside, the potential, and the overall distribution of the outcomes. The pay-off method has been previously applied to a number of corporate finance problems, see, e.g., (Bednyagin & Gnansounou, 2011; Collan, 2011; Hassanzadeh, Collan, & Modarres, 2012). The method has also previously been used in the analysis of the effects of RE incentives on project profitability (Kozlova, Collan, & Luukka, 2015).

Another method that allows for similar distribution-representation of uncertainty is to use simulation based methods, most common of which may be the Monte Carlo simulation that has also previously been used in investment profitability analysis, see, e.g., (Abdel Sabour & Poulin, 2006; Mathews & Salmon, 2007; Mun, 2006). We leave, however, the simulation-based approaches outside the scope of this paper.

The analysis is technically based on a "classical NPV model" that is presented in more detail in (Kozlova, 2015), and the platform used is MS Excel®. The calculation procedure is the typical three-scenario procedure used in connection with the pay-off method that returns triangular distributions, see (Collan, 2012) for details. The case project is assumed to operate in the Russian wholesale power market and falling under the RE capacity mechanism. The electricity wholesale price and the inflation are assumed to be uncertain, and their values are assumed to uniformly distribute (being an interval or a flat distribution) within the ranges between 1-3 rub./kWh and 1-1.7 in terms of the consumer price index, correspondingly. The yield on long-term governmental bonds is assumed to be fixed at 10%. A broad range of possibilities is initially considered for endogenous project factors, such as the capital expenses (CapEx, from a limit of 65.6 min.rub./MW for 2017, set by the legislation, to a level of 150% overspending), the capacity factor (30% - 120% production of the set target that is, 27% for the wind power), and the localization requirement (either "fulfilled" or "failed"), see (Kozlova, 2015) for more details.

By using the above noted initial values in the profitability analysis the pay-off method result is a triangular NPV distribution that is visible in Figure 4, more specifically on the left-most part of the figure, denoted "a". One can see that a major part of the NPV distribution with the initial values discussed above shown in "a" is on the negative side of the zero, which means expectation of loss.

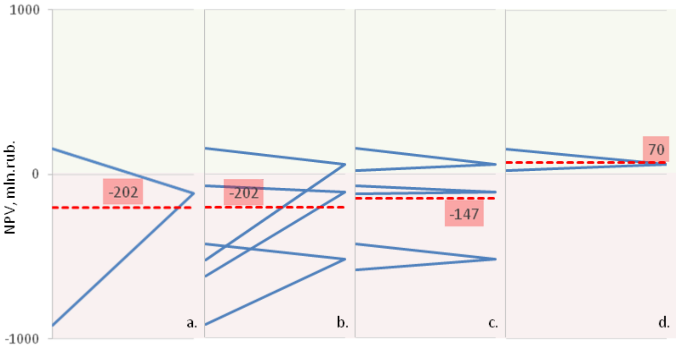

Figure 4. Wind project pay-off distributions for different cases, with mean NPV indicated (dotted line).

The shape of the NPV distribution is caused by the possibility of the combination of a low capacity price, as a result of a low capacity factor, failed localization, and overspent CapEx. If we "divide" the analysis into three sub-analyses, where we use one of the three capacity factor "states" (as described above) in each, we obtain three overlapping NPV distributions, visible in Figure 4 (b) that reflect the three different possible outcomes of the wind farm profitability in the different electricity production performance ranges. Figure 4 (c) illustrates the distributions for the same situation, when the localization requirement is "fulfilled" and the CapEx is "within the set limit" – the uncertainty is reduced (distributions become narrower). One can see that in this case the distribution that results from the "capacity factor ≥75% of the target" – situation, with a full capacity payment, is in its entirety over the positive “zone”, thus signaling that the project is expected to only produce positive NPV outcomes. Figure 4 (d) shows separately the said case with the full capacity payment, with the calculated possibilistic mean value of 70 mln.rub indicated. The internal rate of return (IRR) is 14.5% in this case.

By analyzing the sub-distributions of the “overall situation” separately, in this case by looking at variable´s values “state by state”, one can derive important information about what variable state combinations correspond to profitable vs. unprofitable projects.

What can be seen from the numerical illustration, with regards to the RE capacity mechanism, is that the mechanism, when an investment meets all the targets, is able to guarantee a much lower risk level regardless of market conditions. The illustration, in fact, shows a situation (Figure 4d), where the investment is expected to be profitable in all considered states, when the localization, capacity factor, and CapEx targets are met.

5. Analyzing policy realization

Something that works in a modeling environment, does not necessarily work in reality, Table 2 summarizes the actual results of the two competitive capacity auctions held in 2013 and 2014, each used for selecting renewable energy projects for a period of 4-years-ahead.

Table 2. Selection results, MW.

Technology	Capacity	2014	2015	2016	2017	2018
Wind	target	100	250	250	500	750
	selected	0	51	15	90	0
	%	0%	20%	6%	18%	0%
Solar PV	target	120	140	200	250	270
	selected	35,2	140	189	255	285
	%	29%	100%	95%	102%	106%
Small hydro	target	18	26	124	124	141
	selected	0	0	0	20,64	0
	%	0%	0%	0%	17%	0%

One can observe from Table 2 that the auction results are reassuring from the point of policy success only with regards to solar PV power that has received enough bids for new capacity to be built almost as planned. For wind and small hydro power investments the picture seems bleak. The results may be caused by investments being hindered by the rather strict localization requirements and the strict CapEx limits (Boute, 2014; Gerden, 2014). In addition, the depreciation of the ruble has made the ‘foreign’ part of capital expenses more expensive for Russian companies thus contributing to the difficulty of being able to keep the CapEx below the set limits.

6. Discussion and conclusion

Renewable energy production is actively sought more and more by emerging economies and there are various incentive mechanisms in place to support new RE investments. While most developing countries have adopted approaches that have been previously deployed in developed countries, Russia has followed its own path and extended the existing Russian national capacity and electricity market mechanisms to include incentives for renewable energy investments.

A new capacity based RE incentive mechanism was implemented for the wholesale market within capacity trading in 2013. Selected on annual actions, projects become eligible for long-term capacity contracts that guarantee a specific rate of return on investment for new RE investments, irrespective of market conditions for successful projects that have fulfilled the required quota of Russian national “production” and capital expense limits in the investment phase and that continuously fulfill set production targets. A tariff-based RE incentive mechanism is in force since 2015 on the retail electricity markets, where remuneration is provided in terms of electricity produced from RE sources and also designed to provide some return on investment.

A case illustration that uses the pay-off method was used to show how a project that is able to fulfill the set requirements and targets is able to enjoy a considerable reduction of risks from the RE incentive mechanism.

In reality, there are some challenges impeding renewable energy deployment in Russia. In particular, the strict local content requirement and the capital expenses limit seem to constrain investments into wind and small hydro power projects. Solar PV investments however, seem to be picking up.

This study contributes to the existing academic literature on emerging economies RE investments by presenting the analysis of the two emerging Russian renewable energy support schemes. Further investigation and more detailed modeling of the effects and effectiveness of the Russian RE policy will reveal more insights for investors and for policymakers.

Acknowledgments

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References

1. Abdel Sabour, S. A., & Poulin, R. (2006). Valuing real capital investments using the least-squares monte carlo method. *The Engineering Economist*, 51(2), 141-160.
2. Bednyagin, D., & Gnansounou, E. (2011). Real options valuation of fusion energy R&D programme. *Energy Policy*, 39(1), 116-130.
3. Boute, A. (2012). Promoting renewable energy through capacity markets: An analysis of the Russian support scheme. *Energy Policy*, 46(0), 68-77.
4. Boute, A. (2014). Green energy in Russia: Window-dressing, protectionism or genuine decarbonisation? Retrieved September 2, 2015, from http://russiancouncil.ru/en/inner/?id_4=3286#top-content
5. Collan, M. (2012). The pay-off method: Re-inventing investment analysis. CreateSpace Inc., Charleston.
6. Collan, M. (2011). Valuation of industrial giga-investments: Theory and practice. *Fuzzy Economic Review*, 16(1), 21.
7. Collan, M., Fullér, R., & Mezei, J. (2009). A fuzzy pay-off method for real option valuation. *Journal of Applied Mathematics and Decision Sciences*, 2009, 1-14.
8. Federal Tariff Service, 29 may 2015. Order Draft on Methodology Affirmation on the Electricity Tariff Formation Produced from Renewable Energy Sources and Bought to Compensate Grid Losses.
9. Frankfurt School UNEP Collaborating Centre, & Bloomberg New Energy Finance. (2015). Global trends in renewable energy investment 2015.
10. Gerden, E. (2014). Manufacturers petition Russian government over wind rules. Retrieved September 2, 2015, from http://www.windpowermonthly.com/article/1305696/manufacturers-petition-russian-government-wind-rules?DCMP=EMC-CONWindpowerWeekly&bulletin=windpower-weekly#disqus_thread

11. Gore, O., Viljainen, S., Makkonen, M., & Kuleshov, D. (2012). Russian electricity market reform: Deregulation or re-regulation? *Energy Policy*, 41(0), 676-685.

12. Government of Russian Federation, 28 may 2013(a). Decree #449 on the Mechanism of Promoting the use of Renewable Energy in the Wholesale Market of Electric Energy and Power.

13. Government of Russian Federation, 28 may 2013(b). Resolution #861-R on Amendments being made to Resolution #1-R 8.01.2009 on the Main Directions for the State Policy to Improve the Energy Efficiency of the Electricity Sector on the Basis of Renewable Energy Sources for the Period Up to 2020.

14. Government of Russian Federation, 23 January 2015. Decree #47 on Amendments to some Legislative Acts of Russian Federation on Promotion of Renewable Energy Sources use in Retail Electricity Markets.

15. Hassanzadeh, F., Collan, M., & Modarres, M. (2012). A practical approach to R&D portfolio selection using the fuzzy pay-off method. *Fuzzy Systems, IEEE Transactions On*, 20(4), 615-622.

16. International Finance Corporation. (2011). Renewable energy policy in Russia: Waking the green giant. Retrieved September 2, 2015, from http://www.ifc.org/wps/wcm/connect/6239e00040c80fcdb865bd5d948a4a50/Green+Giant_Eng.pdf?MOD=AJPERES

17. International Finance Corporation. (2013a). Regional renewable energy tariffs in Russia. Retrieved September 2, 2015, from http://www.ifc.org/wps/wcm/connect/bfc20b8040c77040ae2fbf5d948a4a50/Regional+tariffs+report_Eng.pdf?MOD=AJPERES

18. International Finance Corporation. (2013b). Russia’s new capacity-based renewable energy support scheme. An analysis of decree no. 449. Retrieved September 2, 2015, from http://www.ifc.org/wps/wcm/connect/f818b00042a762138b17af0dc33b630b/Energy-Suppor-Scheme-Eng.pdf?MOD=AJPERES

19. Kozlova, M., Collan, M., & Luukka, P. (2015). Comparing Datar-Mathews and fuzzy pay-off approaches to real option valuation. Real Option Workshop, Lappeenranta, Finland. 29-34.

20. Kozlova, M. (2015). Analyzing the effects of the new renewable energy policy in Russia on investments into wind, solar and small hydro power. Master's thesis, Lappeenranta University of Technology, Lappeenranta, Finland. (http://urn.fi/URN:NBN:fi-fe201503171951)

21. Kuleshov, D., Viljainen, S., Annala, S., & Gore, O. (2012). Russian electricity sector reform: Challenges to retail competition. *Utilities Policy*, 23(0), 40-49.

22. Mathews, S., & Salmon, J. (2007). Business engineering: A practical approach to valuing high-risk, highreturn projects using real options. *Tutorials in Operations Research*, 9, 157-175.

23. Mun, J. (2006). Modeling risk: Applying Monte Carlo simulation, real options analysis, forecasting, and optimization techniques. Wiley Finance. John Wiley & Sons, Hoboken, USA.

24. NP Market Council. (2006). Regulations of Financial Arrangements on the Wholesale Energy Market (Appendix #16 to the Agreement for Accession to the Wholesale Market Trading System).

25. NP Market Council. (2012a). Electric power industry of Russia. Retrieved August 13, 2015, from http://www.en.np-sr.ru/abouttheelectricityindustry/abouttheindustry/index.htm

26. NP Market Council. (2012b). Wholesale market. Retrieved August 13, 2015, from http://www.en.np-sr.ru/abouttheelectricityindustry/electricityandcapacitymarkets/wholesalemarket/#3

27. REN21. (2014). Renewables 2014 global status report. Retrieved August 15, 2015, from http://www.ren21.net/Portals/0/documents/Resources/GSR/2014/GSR2014_full%20report_low%20res.pdf

28. Vasileva, E., Viljainen, S., Sulamaa, P., & Kuleshov, D. (2015). RES support in Russia: Impact on capacity and electricity market prices. *Renewable Energy*, 76(0), 82-90.

Publication V

Kozlova M., Collan M., and Luukka P

Comparison of the Datar-Mathews Method and the Fuzzy Pay-Off Method through Numerical Results

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Comparison of the Datar-Mathews method and the Fuzzy Pay-Off method through numerical results

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The authors declare that there is no conflict of interest regarding the publication of this paper.

***Abstract* — The paper compares numerically the results from two real option valuation methods, the Datar-Mathews method and the Fuzzy Pay-Off method. Datar-Mathews method is based on using Monte Carlo simulation within a probabilistic valuation framework, while the Fuzzy Pay-Off method relies on modeling the real option valuation by using fuzzy numbers in a possibilistic space. The results show that real option valuation results from the two methods seem to be consistent with each other. The Fuzzy Pay-Off method is more robust and is usable also, when not enough information is available for a construction of a simulation model.**

Keywords—real option valuation; Datar-Mathews method; fuzzy pay-off method.

1. Introduction

Real option analysis (ROA) is slowly becoming a part of the investment analysis process in companies [1-3], while it has been gaining more and more attention in academia. The reason for excitement around ROA is that it offers the ability to better incorporate uncertainty and to capture the value of managerial flexibility, when the profitability of investments is analyzed [4, 5]. The first models used for numerical real option valuation were models that had been originally designed for the valuation of financial options, namely the Black-Scholes formula [6] and binomial option pricing techniques [7]. These models are still used for a range of valuation problems [8-10]. Later, a number of new real option valuation models, with various model-constructs and modeling choices have emerged [11]. There seems to be a migration by business users of real option analysis away from using the "old" models designed originally for financial option valuation towards the use of simulation based (Monte Carlo) ROV methods [12-18], fuzzy real option valuation [19-26], and models that use system dynamic modeling as the basis for framing the real option analysis [27-30]. The different ROA methods are not necessarily competitors to each other, as the selection of the model used should be made based on the type of uncertainty that surrounds the analyzed investment and hence based on the type of the available information [31].

This paper concentrates on comparatively numerically analyzing two ROA methods, the Datar-Mathews method (DMM) that exploits Monte Carlo simulation in real option valuation [12-14] and the fuzzy pay-off method (FPOM) that is based on using managerially estimated cash-flow scenarios represented as fuzzy numbers, as the basis for real option valuation [19-22]. Both methods have similar real option valuation logic [31], but are based on a different set of modeling choices. The Datar-Mathews method is usable under the assumption that there is enough information available for the construction of a credible model to underlie a Monte Carlo simulation, while the fuzzy pay-off method is usable also in situations, where only information that is in the form of expert estimates about future cash-flows is available.

This research, of which initial ideas are reported in [32], presents the comparison of these two methods by investigating the difference between the final resulting real option values and by studying the generated distributions used in these two methods. Comparison of the (mathematical) structure of the two methods is left outside the scope of this paper. Two investment cases are used in the analysis that both are based on a solar photovoltaic power generation investment, but under two different regimes of support mechanism for the investment. This paper continues in vein with other recent research on the usability of the fuzzy pay-off method as a tool for real option valuation, see [33].

This paper continues by presenting the constructs of the Datar-Mathews method and of the fuzzy pay-off method, followed by two case-based numerical illustrations that are used to showcase the practical use of the methods. Then the results from the numerical illustrations are compared and finally the paper is closed with a discussion and conclusions.

2. The two methods shortly presented

In this part, we describe the structures of the two compared ROA methods, the Datar-Mathews method and the fuzzy pay-off method.

2.1. The Datar-Mathews method

Datar-Mathews real option valuation method [12] (DMM) is based on using Monte Carlo simulation to capture the uncertainty found in investments projects. Typically, when the method is used, a net present value profitability analysis model is used. It is often the case that businesses have such a model already in place and it can be used as a starting point for the Datar-Mathews ROA. The model construct typically includes the important profitability-affecting variables for the costs and for the revenues that together form the basis for calculating yearly cost and revenue cash-flows from an investment project. The yearly cost and revenue cash-flows are discounted by using separate discount rates, typically one for the costs and one for the revenues. The idea with using separate cash-flows is that the cost and the revenue cash-flow "processes" are not the same and that their risk-levels are different. The Datar-Mathews ROV procedure includes the following steps (we assume that a calculation model is in place):

1. Managers are asked to define the type and details of the distribution of the possible values for each model input variable, from which the simulation procedure randomly draws values.
2. Simulation is run to generate a sufficient number of (typically thousands) pseudo-random profitability (NPV) outcomes with the model. From the outcomes a histogram is compiled, which is treated as a probability distribution of the project NPV pay-off.
3. The DMM treats the project as an option and in order to "move" from the NPV pay-off distribution to an option pay-off distribution the sub-zero outcomes from the project are mapped to zero, while they keep their original probability weight. This means that all the negative outcomes´ weights are truncated to zero.
4. The real option value (ROV) is calculated as the mean of the resulting option pay-off distribution.

Under these circumstances the real option value of the project can be formulated as [12]:

'Risk Adjusted Success Probability x (Benefits – Costs)' (1)

The Datar-Mathews method is a relatively simple method for the user. In addition to the needed discounted cash-flow the user must have the capability to use a standard Monte Carlo simulation. Typically the analysis is conducted on a spread-sheet software. The method has previously been used, e.g., in the valuation of aircraft development projects [12, 13, 34], analysis of prognostic technology in health management [35], and in the evaluation of renewable energy projects [36].

2.2. Fuzzy pay-off method

Fuzzy pay-off method [19] (FPOM) is based on using managerially given cash-flow scenarios that typically consist of yearly cash-flow estimates from a project as the starting point. The estimated cash-flows are used in an NPV valuation of each scenario. From the scenario NPVs a fuzzy number pay-off distribution for the project is generated. From the created fuzzy pay-off distribution the project real option value is calculated. The procedure used in the fuzzy pay-off method can be expressed shortly as:

1. Three or four scenarios of the future project cash-flow streams are estimated. Typically the managers are asked to provide estimates for a "minimum possible" and a "maximum possible", and one or two "best estimate" scenarios. The estimated cash-flows are used in the calculation of the NPV for each scenario. Revenues and costs may be estimated separately and separate discount rates may be used for revenues and costs. The link between the operational costs and the revenues must be properly scrutinized, see [20];
2. A fuzzy pay-off distribution for the project is constructed from the scenario NPVs. As three or four scenarios are typically used the fuzzy pay-off distribution is either triangular or trapezoidal. The minimum possible and maximum possible scenario NPVs are considered to establish the lower and the upper limits of the distribution and they are assigned a limit to zero degree of membership in the set of possible NPV outcomes. The best estimate value(s) is assigned full membership;
3. The real option value is directly calculated from the fuzzy pay-off distribution. The formula used adheres to the typical real option valuation logic and is simply the possibilistic mean of the positive side of the distribution weighted by the project "success ratio". The project success ratio is the area of the pay-off distribution over the positive side, divided by the total area of the pay-off distribution, see equation (2) below.

$$ROV = E(A^{+}) * \frac{A^{+}}{A} \tag{2}$$

Details of the fuzzy pay-off method can be found in [19], while the original resource for the possibilistic mean used is given in [37]. What can be said about the procedure used, when using the method is that it is simple and the computational procedure does not require "any" computing power. The fuzzy pay-off method has been applied to several real-word problems, including the analysis and selection of R&D projects [38, 39], the analysis of large industrial investments [25, 40], and patent valuation [24].

3. Numerical case-based illustration of the two methods and comparison of the results

Two investment cases are used to compare results derived with the two methods. The investment cases are both industrial-scale investment projects into a solar photo-voltaic (PV) power plant, but under different renewable energy supporting schemes (subsidy schemes).

The first case analyzes an investment that falls within the scope of the Russian renewable energy (RE) support mechanism, based on long-term capacity contracts and with a rather complex incentive system. A guaranteed capacity price within these contracts is calculated by the regulating authority, as a variable rate annuity that is designed to provide a certain level of return on investment. The scheme takes into account changing market conditions and the project-specific performance [41, 42]. For more information about the Russian RE investment incentive mechanisms see [43-46].

The second case represents an investment into the same project under a simpler generic feed-in premium RE incentive scheme, such that is being used more generally in Europe. The used incentive scheme guarantees a fixed premium over the spot electricity price over the long term (for the calculations twenty years are assumed). For the purposes of this illustration, the premium level is set in a way that it provides approximately the same level of profitability as the first case. This has no importance for the comparison of the results from the point of view of the comparative analysis of the two real option analysis methods, but allows the comparison of the two RE incentive mechanisms for those interested. A more detailed description of the two cases and the set of assumptions made can be found in [36].

A typical "classical" NPV investment profitability analysis calculation model is used in both cases. The software used is Microsoft Excel® for the analyses with the fuzzy pay-off method and Matlab Simulink® for the analyses with the Datar-Mathews method. Even if the software used to run the analysis is different the model used is identical. The information used in creating the three needed scenarios for the fuzzy pay-off method is presented in Table 1.

TABLE 1. UNCERTAIN FACTORS, SEE [31] FOR DETAILS

Factor	**Range of values**		
	Pessimistic	***Best-estimate***	***Optimistic***
Electricity price, rub./MWh	1000	2000	3000
Consumer price index (inflation)	1.70	1.35	1.00
CapEx level	150%	100%	80%
Capacity factor (percent of target)	30%	75%	120%
Localization requirement	Failed	Fulfilled	Fulfilled

The same values (Table 1) are also used as the basis for the pseudo-random distribution, from which the Monte Carlo simulation used in the Datar-Mathews method draws the random outcomes for these variables. Uniform distributions between the "pessimistic" and "optimistic" values are used in the illustration. One hundred thousand rounds of simulation are run for both cases. In the generic feed-in premium case, the "localization requirement" variable is not used.

A. *Numerical results of the two cases and a comparison of the methods based on the results*

Results for the first case, with the two methods are presented in Fig. 1. Figure 1a shows a histogram that has been generated from the results of the Monte Carlo simulation used in the Datar-Mathews method, the expected NPV and ROV are shown with dashed lines. Figure 1b shows the triangular NPV distribution constructed, when using the fuzzy pay-off method, with the expected NPV and the calculated ROV values. Figure 1c shows a stylized overlap of the two graphs.

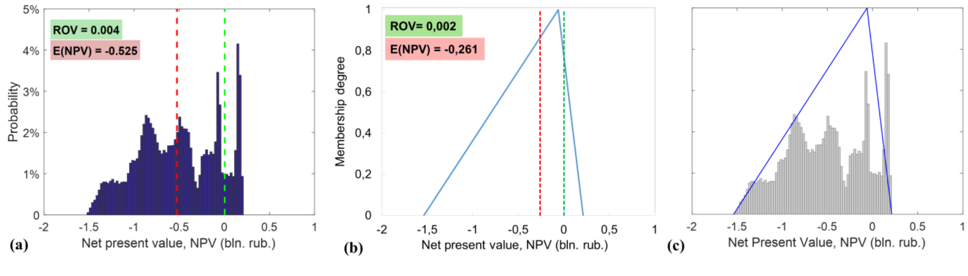

Fig. 1. NPV distributions for the first case. (a) simulated NPV distribution, (b) triangular fuzzy NPV, and (c) stylized plot of both distributions on the same graph. Dashed lines: red – expected NPV, green – ROV.

One can observe that the lowest and the highest values of the distributions match, which is expected, but in this case the shapes of the two distributions are very different. The rather complex construct of the underlying Russian RE incentive mechanism causes the shape of the simulated NPV pay-off histogram of the project to be atypical with multiple summits. This indicates that there are local maxima that the Monte Carlo simulation used in the Datar-Mathews method can capture. At the same time it is quite clear that the fuzzy pay-off method may be too robust for the complex problem. What is interesting is that the real option valuation result is nevertheless similar in absolute numbers, see also Table 2.

Results for the second case, an investment into a renewable energy project with a generic feed-in premium incentive system are presented in Figure 2. In Figure 2a the histogram generated from the results of the Monte Carlo simulation for the Datar-Mathews method is visible. Again the expected (single number) NPV and the ROV are shown as dashed lines. The shape of the simulated distribution is more “typical” as there are no “conditioning” variables that would cause the distribution to exhibit multiple summits. Figure 2b exhibits the triangular distribution constructed with the fuzzy pay-off method and Figure 2c shows a stylized overlap of the two graphs.

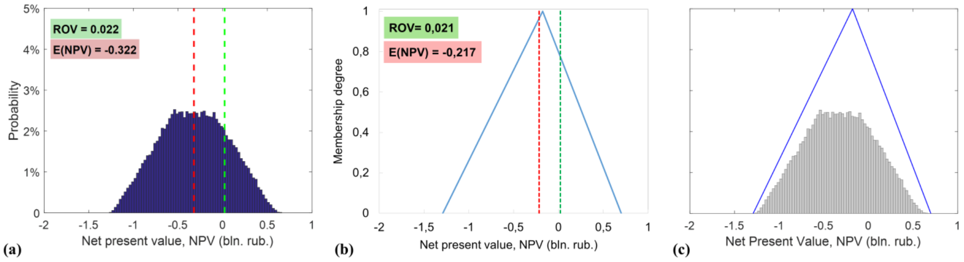

Fig. 2. NPV distributions for the second case. (a) simulated NPV distribution, (b) triangular fuzzy NPV, and (c) stylized plot of both distributions on the same graph. Dashed lines: red – expected NPV, green – ROV.

As in the first case the “limits” or the extreme high and low values of the distributions are almost equal, again this was expected, however the shapes of the two distributions are much more uniform than in the first case. This can be interpreted in the way that the problem complexity is at a level that is suitable also for the more robust fuzzy pay-off method. The results from the two methods are more similar to each other in the second case than in the first case, this indicates that when the type of problem analyzed is relatively simple the precision of the fuzzy pay-off method can be considered to be satisficing. The difference between the ROV in the second case is negligible. Lilliefors test shows that the simulated distributions in both cases are not “normal”. Descriptive statistics for the two cases are collected into Table 2 for easy comparison.

TABLE 2. COMPARISON OF RESULT STATISTICS (IN RUB. BLN.)

	First case			Second case		
	DMM	FPOM	difference	DMM	FPOM	difference
ROV	0,004	0,002	0,002	0,022	0,021	0,001
E(NPV)	-0,525	-0,261	0,264	-0,322	-0,217	0,105
Standard deviation (x100%)	0,441	0,358	0,083	0,384	0,406	0,022
“Success ratio”	3 %	9 %	6 %	11 %	28 %	17 %

Table 2 clearly shows that the results from the two methods are not equal. It would have been very surprising, if they were, as the construct and the degree of simplification is different. What can be however seen is that the results, especially for the ROV are surprisingly similar in both cases. Otherwise, the descriptive statistics for the second case are more similar between the two methods, this can be attributed to the simpler problem structure.

Despite the comparable numeric indicators, the DMM and the FPOM are substantially different in terms of their implementation and computational performance (Table 3).

TABLE 3. COMPARISON OF DMM AND FPOM PERFORMANCE

	DMM	FPOM
Computational time (first case), s.	6,19	0,11
Computational time (second case), s.	1,01	0,04
Ease of implementation	Requires a simulation software and the skills to use it	Simple spreadsheet software is enough
Information content of results	Histogram of the outcome, ability to capture irregularities of complex problems, e.g., step-causal or nonlinear interdependency of variables	A triangular pay-off distribution has a fixed form regardless of the problem complexity, a simplification of results

The computational time to run both analyses is short, but the simulation used in the DMM is time consuming, it takes roughly 25-50 times more time than running three scenario calculations for the FPOM. The simulation time depends on the complexity of the problem. In addition, implementing the DMM requires building a model in a computational environment with Monte Carlo simulation capability and requires the user of the model to have the required skills to build simulation models and to run them. In contrast, the FPOM can be easily implemented with spreadsheet software, without any special skills.

The findings presented here support the previous findings [33] on the practical usability of the fuzzy pay-off method, when the type of information available and the problem structure is robust.

4. Conclusions

The Datar-Mathews and the fuzzy pay-off method are both relatively new real option analysis methods that have been constructed, while keeping in mind managerial users. Both exploit the well-known real option valuation logic, but are based on different theoretical foundations in terms of their computational procedure. The Datar-Mathews method is a simulation based method that treats uncertainty in terms of probability theory, while the fuzzy pay-off method is a more robust method based on using fuzzy number representations of cash-flow information.

This paper has demonstrated with numerical illustrations the application and usability of these two methods in the analysis of two investment cases with different levels of complexity. The comparative analysis of the results of these analyses reveals that while the pay-off method simplifies the analysis, it still seems to offer sufficient precision for the analysis of problems with low complexity. On the other hand, the simulation-based Datar-Mathews method is able to treat problems that have more complex structures, but requires more computational time and specialized software. The overall results obtained in terms of real option valuation show that the two methods return similar results. One has to observe that the two presented cases are not enough to draw definitive conclusions on the matter, but illustrate well the difference in how robust these methods are.

The work presented in this paper can be used in understanding better the kinds of problems these methods are good for. The results are of use for practitioners navigating selection of proper valuation technique and support earlier findings on the usability of these methods. The comparison of these methods with other methods merits further study and specifically the amount of complexity and type of uncertainty that different methods can handle in terms of credible and usable results. In more general terms the study of the usability of different analysis real option analysis methods is a topic that has been “under studied” in the past.

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References

[1] P.A. Ryan and G.P. Ryan, "Capital budgeting practices of the Fortune 1000: how have things changed," Journal of Business and Management, vol. 8, pp. 355-364, 2002.
[2] S. Block, "Are “real options” actually used in the real world?" The Engineering Economist, vol. 52, pp. 255-267, 2007.
[3] J.R. Graham and C.R. Harvey, "The theory and practice of corporate finance: evidence from the field," J.Financ.Econ., vol. 60, pp. 187-243, 5. 2001.
[4] L. Trigeorgis, Real options: an overview, Praeger Westport, CT, 1995, .
[5] M. Amram and N. Kulatilaka, Real Options:: Managing Strategic Investment in an Uncertain World, Oxford University Press, 1998, .
[6] F. Black and M. Scholes, "The pricing of options and corporate liabilities," The Journal of Political Economy, pp. 637-654, 1973.
[7] J.C. Cox, S.A. Ross and M. Rubinstein, "Option pricing: A simplified approach," . Journal of Financial Economics, vol. 7, pp. 229-263, 1979.
[8] A.A. Gray, P. Arabshahi, E. Lamassoure, C. Okino and J. Andringa, "A real options framework for space mission design," in 2005 IEEE Aerospace Conference, pp. 137-146, 2005.
[9] B. Kim, H. Lim, H. Kim and T. Hong, "Determining the value of governmental subsidies for the installation of clean energy systems using real options," J.Constr.Eng.Manage., vol. 138, pp. 422-430, 2012.
[10] S.L. MacDougall, "The value of delay in tidal energy development," Energy Policy, vol. 87, pp. 438-446, 2015.
[11] L. Trigeorgis, Real options: Managerial flexibility and strategy in resource allocation, MIT press, 1996, .
[12] S. Mathews, V. Datar and B. Johnson, "A Practical Method for Valuing Real Options: The Boeing Approach," J.Appl.Corp.Finance, vol. 19, pp. 95-104, 2007.

[13] S. Mathews and J. Salmon, "Business engineering: a practical approach to valuing high-risk, highreturn projects using real options," Tutorials in Operations Research, vol. Chapter 9, pp. 157-175, 2007.
[14] V.T. Datar and S.H. Mathews, "European real options: An intuitive algorithm for the Black-Scholes formula," Journal of Applied Finance, vol. 14, pp. 45-51, 2004.
[15] C. Bastian-Pinto, L. Brandão and W.J. Hahn, "Flexibility as a source of value in the production of alternative fuels: The ethanol case," Energy Economics, vol. 31, pp. 411-422, 2009.
[16] T.K. Boomsma, N. Meade and S. Fleten, "Renewable energy investments under different support schemes: A real options approach," Eur.J.Oper.Res., vol. 220, pp. 225-237, 7/1. 2012.
[17] M. Monjas-Barroso and J. Balibrea-Iniesta, "Valuation of projects for power generation with renewable energy: A comparative study based on real regulatory options," Energy Policy, vol. 55, pp. 335-352, 4. 2013.
[18] W.H. Reuter, S. Fuss, J. Szolgayová and M. Obersteiner, "Investment in wind power and pumped storage in a real options model," Renewable and Sustainable Energy Reviews, vol. 16, pp. 2242-2248, 5. 2012.
[19] M. Collan, R. Fullér and J. Mezei, "A fuzzy pay-off method for real option valuation," Journal of Applied Mathematics and Decision Sciences, vol. 2009, pp. 1-14, 2009.
[20] M. Collan, "The pay-off method: Re-inventing investment analysis," CreateSpace Inc., Charleston, NC, USA, 2012.
[21] J. Mezei, "A quantitative view on fuzzy numbers," pp. 191, 2011.
[22] C. Carlsson and R. Fullér, Possibility for decision: a possibilistic approach to real life decisions, Springer Science & Business Media, 2011, .
[23] F. Hassanzadeh, M. Collan and M. Modarres, "A practical R&D selection model using fuzzy pay-off method," The International Journal of Advanced Manufacturing Technology, vol. 58, pp. 227-236, 01/01. 2012.
[24] M. Collan and M. Heikkilä, "Enhancing patent valuation with the pay-off method," Journal of Intellectual Property Rights, vol. 16, pp. 377-384, 2011.
[25] M. Collan, "Valuation of industrial giga-investments: theory and practice," Fuzzy Economic Review, vol. 16, pp. 21, 2011.
[26] D. Allenotor, A fuzzy real option model for pricing grid compute resources, University of Manitoba, 2011, .
[27] S. Johnson, T. Taylor and D. Ford, "Using system dynamics to extend real options use: Insights from the oil & gas industry," in International system dynamics conference, pp. 23-27, 2006.
[28] B. O'Regan and R. Moles, "A system dynamics model of mining industry investment decisions within the context of environmental policy," J.Environ.Plann.Manage., vol. 44, pp. 245-262, 2001.
[29] P. Sontamino and C. Drebenstedt, "A Prototype Decision Making Tool of Coal Mine Planning Using System Dynamics Model," in Mine Planning and Equipment Selection, Springer, 2014, pp. 1475-1484.
[30] B. Tan, E.G. Anderson, J.S. Dyer and G.G. Parker, "Evaluating system dynamics models of risky projects using decision trees: alternative energy projects as an illustrative example," System Dynamics Review, vol. 26, pp. 1-17, 2010.
[31] M. Collan, "Thoughts about selected models for the valuation of real options," Acta Universitatis Palackianae Olomucensis.Facultas Rerum Naturalium.Mathematica, vol. 50, pp. 5-12, 2011.
[32] M. Kozlova, M. Collan and P. Luukka, "Comparing Datar-Mathews and fuzzy pay-off approaches to real option valuation," in *Real Option Workshop*, pp. 29-34, 2015.
[33] G. Favato, J. Cottingham and N. Isachenkova, "Blending scenarios into real options: relevance of the pay-off method to management investment decisions," Journal of Finance and Accounting, vol. 3, pp. 12-17, 2015.
[34] S. Mathews, "Valuing risky projects with real options," Research-Technology Management, vol. 52, pp. 32-41, 2009.
[35] P. Lall, R. Lowe, K. Goebel and W. Cooper, "Cost assessment for implementation of embedded prognostic health management for electronic systems," in Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm), 2012 13th IEEE Intersociety Conference on, pp. 487-497, 2012.
[36] M. Kozlova, "Analyzing the effects of the new renewable energy policy in Russia on investments into wind, solar and small hydro power," pp. 104, 2015.
[37] C. Carlsson and R. Fullér, "On possibilistic mean value and variance of fuzzy numbers," Fuzzy Sets Syst., vol. 122, pp. 315-326, 2001.
[38] D. Bednyagin and E. Gnansounou, "Real options valuation of fusion energy R&D programme," Energy Policy, vol. 39, pp. 116-130, 2011.
[39] F. Hassanzadeh, M. Collan and M. Modarres, "A practical approach to R&D portfolio selection using the fuzzy pay-off method," Fuzzy Systems, IEEE Transactions On, vol. 20, pp. 615-622, 2012.
[40] M. Kozlova, M. Collan and P. Luukka, "Renewable Energy in Emerging Economies: Shortly Analyzing the Russian Incentive Mechanisms for Renewable Energy Investments," in International Research Conference "GSOM Emerging Markets Conference-2015: Business and Government Perspectives", 2015.
[41] Government of Russian Federation, "28 May 2013 Decree #449 on the mechanism of promoting the use of renewable energy in the wholesale market of electric energy and power," 2013.
[42] Government of Russian Federation, "28 May 2013 Resolution #861-r on amendments being made to Resolution #1-r 8.01.2009 on the main directions for the state policy to improve the energy efficiency of the electricity sector on the basis of renewable energy sources for the period up to 2020," 2013.
[43] A. Boute, "Promoting renewable energy through capacity markets: An analysis of the Russian support scheme," Energy Policy, vol. 46, pp. 68-77, 7. 2012.
[44] E. Vasileva, S. Viljainen, P. Sulamaa and D. Kuleshov, "RES support in Russia: Impact on capacity and electricity market prices," Renewable Energy, vol. 76, pp. 82-90, 4. 2015.

[45] International Finance Corporation, "Russia’s New Capacity-based Renewable Energy Support Scheme. An Analysis of Decree No. 449," vol. 2015, 2013.

[46] M. Kozlova and M. Collan, "Modeling the effects of the new Russian capacity mechanism on renewable energy investments," Energy Policy, vol. 95, pp. 350-360, 2016.

Publication VI

Kozlova M., Collan M., and Luukka P

Simulation decomposition: new approach for better simulation analysis of multi-variable investment projects

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SIMULATION DECOMPOSITION: NEW APPROACH FOR BETTER SIMULATION ANALYSIS OF MULTI-VARIABLE INVESTMENT PROJECTS

M. Kozlova[a], M. Collan[b], P. Luukka[c]

This paper presents a new method to enhance simulation-based analysis of complex investments that contain multi-variable uncertainty. The method is called “simulation decomposition”. Typically the result of simulation-based investment analysis is in the form of histogram distributions - here we propose a method for first classifying the possible outcomes of selected uncertain variables into states and then using combinations of the created states in the decomposition of the simulated distribution into a number of sub-distributions. The sub-distributions that can be matched to state-combinations of the variables contain relevant actionable information that helps managers in decision-making with regards to the studied investments.

A numerical illustration of a renewable energy investment is used to demonstrate the usability, the enhanced analytical power, and the intuitively understandable benefits that can be reached by using the simulation decomposition method. The proposed method is generally usable and can be utilized independent of the investment context.

Keywords: *corporate finance and governance, capital budgeting, simulation modeling, renewable resources and conservation*

JEL Classification: *G31, C15*

1. INTRODUCTION

In this paper we are interested in exploring how typical simulation based investment analysis can be enhanced to offer better managerial decision-support in terms of providing better actionable information about threshold values for

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identified important-to-the-investment variables that affect investment profitability.

Our focus is on analysis that is performed before the investment decision. The decision support before investment is “actionable”, because it is before the investment that decision managers are often in a position that allows them to still plan and steer investments towards the most profitable configurations, and by their actions ensure that critical to profitability issues are properly accounted for.

What we propose is a new approach that we call “simulation decomposition”. The method is based on setting artificial (expert chosen) thresholds to divide the possible value distributions of the most important uncertain variables of an analyzed investment. Typically in Monte Carlo simulation these distributions are from where the simulator draws random variable values. After having “decomposed” each variable´s uncertainty, or “range”, into sub-ranges, the combinations of these sub-ranges are listed. When the simulation is run, the results are registered separately for each combination, in addition to the overall simulation results. This allows for constructing a separate distribution of outcomes for each combination that is a sub-distribution of the overall simulation result. By studying the sub-distributions managers can infer important information about the profitability-critical threshold values for each variable that will help them plan their actions with regards to managing the investment better.

Modern investment decision-making is most often an exercise that involves comparing the value of an upfront investment cost and a stream of uncertain future cash-flows that is expected to result from the prospective investment. In practice, the methods “used for the job” are the “classical” capital budgeting methods, such as the net present value (NPV) method, the pay-back method, and the internal rate of return method (IRR) that are often used together with complementary sensitivity, scenario, and simulation analysis methods (Block, 2007; Graham and Harvey, 2001; Ryan and Ryan, 2002). Real option analysis (Amram and Kulatilaka, 1998; Trigeorgis, 1995) is among the latest additions into the investment analysis toolkit of managers and has been gaining a foothold in academic research, as well as, a following in the industry. The benefit of real option analysis over the classical methods is that it is able to capture the value of managerial flexibility that is to be found within investments, and when investments are considered as a whole. Often a mixture of different investment analysis techniques is used simultaneously in hopes of gaining a better holistic picture of the situation surrounding the investment and in order to comprehensively treat the risks involved.

Simulation and more specifically Monte Carlo simulation (commonly attributed to Stanislaw Ulam), is a technique that has been used in asset valuation since the late 1970´s, e.g., (Boyle, 1977), and in investment analysis of real investments for more than two decades. In connection with the classical profitability analysis methods simulation has been used, e.g., in enhancing scenario analysis for complementing the investment analysis (Sheel, 1995). Simulation has also been used together with dynamic system models in investment analysis and profitability evaluation of, e.g., mining and oil investments (Johnson *et al*., 2006; O'Regan and Moles, 2001; O'Regan and Moles, 2006; Sontamino and Drebenstedt, 2014; Tan, Anderson *et al*., 2010), and to offer a better understanding of how uncertain variables affect profitability of energy investments (Bastian-Pinto, *et al*., 2010; Boomsma *et al*., 2012; Kozlova *et al*., 2015; Monjas-Barroso and Balibrea-Iniesta, 2013; Reuter *et al*., 2012; Vithayasrichareon and MacGill, 2012; Yang *et al*., 2010). Simulation is also an underlying technique in many modern real option valuation methods such as the Datar-Mathews method (Datar and Mathews, 2004; Mathews *et al*., 2007) and the Matching Method (Jaimungal and Lawryshyn, 2015). Typically what is achieved as an end result from a simulation based profitability analysis is a histogram (distribution) of project profitability, a NPV distribution. Simulation is also used in many fields of engineering as a standard multi-purpose tool; these other purposes are however left outside the scope of this paper, but we suggest the interested reader to see, e.g., (García-Redondo *et al*., 2012; Rane *et al*., 2014). The proposed method may be useful in providing new insight in such simulation-based analysis as e.g. (Nembhard *et al*., 2003; Ridlehoover, 2004; Savolainen *et al*., 2016).

Although the Monte Carlo simulation technique has been applied to many different problems throughout the years, the simulation method itself and the way the simulation results are analyzed has remained relatively unchanged. Here we propose an enhancement to the simulation procedure and as a consequence to the analysis of the received results that enhances the explanatory power of the results in terms of increased understanding of the cause-effect relationship between the variables and the simulation results.

The proposed new approach is illustrated numerically with a case that is based on a renewable energy investment into Russia that may enjoy the support offered by the Russian renewable energy incentive mechanism (Government of Russian Federation, 2013a; Government of Russian Federation, 2013b). The case is especially suitable for the task, as the complex incentive mechanism “naturally” creates what can be called artificial thresholds for the variables that are important to the profitability of the investment (Boute, 2012; International Finance Corporation, 2011; Kozlova, 2015; Vasileva *et al*., 2015).

The remainder of the paper is structured as follows: the following section presents the proposed simulation approach in more detail, then a numerical case illustration based on a renewable energy investment in Russia is presented to show real-world use of the approach, and finally conclusions are drawn and some future research directions are identified.

2. THE NEW SIMULATION DECOMPOSITION APPROACH

It needs to be observed first that we expect that a simulation model has been built and on the model one can run Monte Carlo simulation. As this is in place we directly present how the simulation procedure is to be changed according to the simulation decomposition approach. In order to do this the simulation decomposition process is presented as a five step algorithm:
Step 1: Identify key variables $\widetilde{V}_i$ and the possible range of the values that each identified key variable can take.

The first step is to start from identifying key variables, where important to the project profitability uncertainty exists. These can be identified by consulting the managers inside the organization involved in the planning of the investment project, or by simply performing typical sensitivity analysis to find out which variables are the most important. These variables are "the same variables" that would "normally" be identified, when a classical Monte Carlo simulation model is built, and for which values are simulated. In the case example used in this paper five uncertain key variables were identified. After identification, the range of values that each identified key variable may have is estimated. The determination of the ranges can be done by asking managers to identify them by, for example, giving minimum and maximum possible values for each variable, or by deriving the range from historical data. It is worth mentioning that only this first step belongs also to the procedure used in the classical Monte Carlo simulation (Mooney, 1997), while the rest form a unique basis for the decomposition approach.

Step 2: Identify key variables that the organization can affect and relevant states $\widetilde{A}_{ij}$ for these.

The second step in the simulation decomposition approach is to identify two, or more, "managerially relevant" states $\widetilde{A}_{ij}$ for the identified key variables that the organization undertaking the project can affect. This part of the process is specific to each problem under analysis, but the point is that the identified states point to different outcomes in terms of project success, or organizational achievement in terms of the variable in question. For instance, in the example used in this paper, states of "failure" or "success" can be identified with regards to reaching a level of production that "earns" the project a subsidy. Typically, when there are no naturally "given" or derivable states they can be managerially determined, based perhaps on issues such as, "certainly reachable" variable values, "usual" or "normal" values of a variable, "good" or "sufficient" variable values, and so forth. The number of identified states may very well be only two, for example, "good" and "bad" – this is not a problem in terms of how the simulation decomposition approach can be used. In the case example used in this paper one identified key variable has three states and two key variables have two states.

States are not identified for variables whose values the organization cannot affect, such as market prices.

Step3: Identify suitable boundaries $\tilde{B}_{ij}$ for each state $\tilde{A}_{ij}$.

The third step of the decomposition analysis is to identify the boundaries $\tilde{B}_{ij}$ between the identified states $\tilde{A}_{ij}$. For binary variables the boundary is naturally between the two state $\tilde{B}_{ij} =$ eas, if one is dealing with a real valued variable, boundaries of the variable are specified by using a threshold value $\tilde{t}_i$, e.g., $\tilde{B}_{i1}=[0,\tilde{t}_i]$ $\tilde{B}_{i2}=(\tilde{t}_i,100]$, where the two identified states of the variable $\tilde{V}_i$ for which the range of possible outcomes is [0,100] (for example %) are separated by the threshold value $\tilde{t}_i$. Similarly $(N_i$-1) threshold values are identified for ith variable with more than two states. For the purposes of this research we focus on using crisp threshold values, uncertainty can be introduced in the threshold values i.e. by using fuzzy sets, but we leave discussion about fuzzy threshold values as a matter of further research and outside the scope of this research.

Step 4: Form groups $\tilde{G}_k$ of combinations to specify the to-be-decomposed parts of the simulation.

The fourth step is to form relevant groups $\tilde{G}_k$ of possible outcomes to investigate by selecting a possible state $\tilde{A}_{ij}$ from each variable $\tilde{V}_i$. The resulting list of groups represents all possible combinations of the states of the key variables. The total number of groups is, therefore, a product of a number of the states of the key variables, $\prod_{i=1}^{n} N_i$, where N_i denotes the number of states in ith variable. For example, having two key variables $\tilde{V}_1$ and $\tilde{V}_2$ with two states identified for each variable, the total number of groups is four and is comprised of $\tilde{G}_1=\{\tilde{A}_{11},\tilde{A}_{21}\}$, $\tilde{G}_2=\{\tilde{A}_{11},\tilde{A}_{22}\}$, $\tilde{G}_3=\{\tilde{A}_{12},\tilde{A}_{21}\}$, $\tilde{G}_4=\{\tilde{A}_{12},\tilde{A}_{22}\}$ (where first index stands for the variable index and the second one for the state). Each group corresponds to a piece of the total simulation, what is essentially done is a specification of the to-be-decomposed parts of the simulated (NPV) distribution for the project.

Step 5: Run the simulation model, while assigning the result of each simulation round not only to the distribution of the “full” simulation, but also to the specified decomposed group $\tilde{G}_k$ or sub-distribution of the simulation.

The fifth step is to run the simulation model n times and to track the resulting NPV value of each simulation round and to store it not only as a part of the “full” NPV distribution from the project, but also as a part of a specifically identified “decomposed” NPV sub-distribution NPV_k (here NPV_k denotes NPV of group $\tilde{G}_k$). The identification of the correct sub-distribution for each round is done by mapping randomly drawn values from each variable $\tilde{V}_i$ to its corresponding state $\tilde{A}_{ij}$ and finding a correct group $\widetilde{G}_k$ by matching states $\tilde{A}_{ij}$ with corresponding group $\tilde{G}_k$. In practice this can be established, for example, by using lookup tables, or by running an if-loop over the variables to find, which particular states are valid for a given round of the simulation run. This way we end up with having $\prod_{i=1}^{n} N_i$ sub-distributions.

For all steps 1-5, $i=1,\cdots,n$; $j=1,\cdots,N_i$; $k=1,\cdots,\prod_{i=1}^{n} N_i$, n is number of variables, and N_i is number of possible states in i^{th} variable.

After this five-step approach is run, one is left with a typical simulated (NPV) distribution for the (whole) project and $\prod_{i=1}^{n} N_i$ sub-distributions, NPV_k, each specified for a particular group $\widetilde{G}_k$. These can then be used to help plan the managerial actions connected to the prospective investment and to understand better the drivers of the profitability of the investment. The simulation decomposition approach can be easily used on top of almost any existing simulation model. The method is also flexible in terms of the software environment used. The main requirement for successfully implementing the method on top of a suitable existing simulation model is constructing a block that matches the (NPV) result of each simulation round with the correct sub-distribution.

3. NUMERICAL CASE ILLUSTRATION

The case used to illustrate the method is an analysis of a renewable energy (RE) investment into a 10MW solar photo-voltaic (PV) power plant in Russia. The revenues from this investment comprise of electricity sales in the Russian wholesale energy market and of subsidy cash-flows from a long-term capacity delivery contract. The latter is calculated based on the rules laid-out in the Russian law governing the incentive mechanism for RE investments that has the target of providing a certain level of return on investment. The mechanism considers changing market conditions and project-specific characteristics, for details see (Government of Russian Federation, 2013a; Government of Russian Federation, 2013b). The Russian mechanism is different from the typically used RE incentive schemes in use, e.g., in Central Europe. For more on the Russia RE support mechanisms see (Boute, 2012; International Finance Corporation, 2011; Kozlova, 2015; Vasileva *et al*., 2015).

The investment analysis model for the solar power plant investment is a simple system dynamic model that combines a typical discounted cash-flow calculation with a model of the Russian RE investment incentive mechanism. Block diagram of the model used is presented in Figure 1, where input variables are located on the left-hand side of the model and outputs are visible on the right. The two largest blocks represent the main computational parts of the model, where the effects of the incentive mechanism are determined for each simulation run and the resulting project NPV are calculated. A more detailed description of the case and the assumptions behind the model used can be found in (Kozlova, 2015).

The model has been built in Matlab Simulink and the simulations are run ten thousand times (rounds). Next we go through the simulation decomposition procedure in the order of the algorithm presented above.

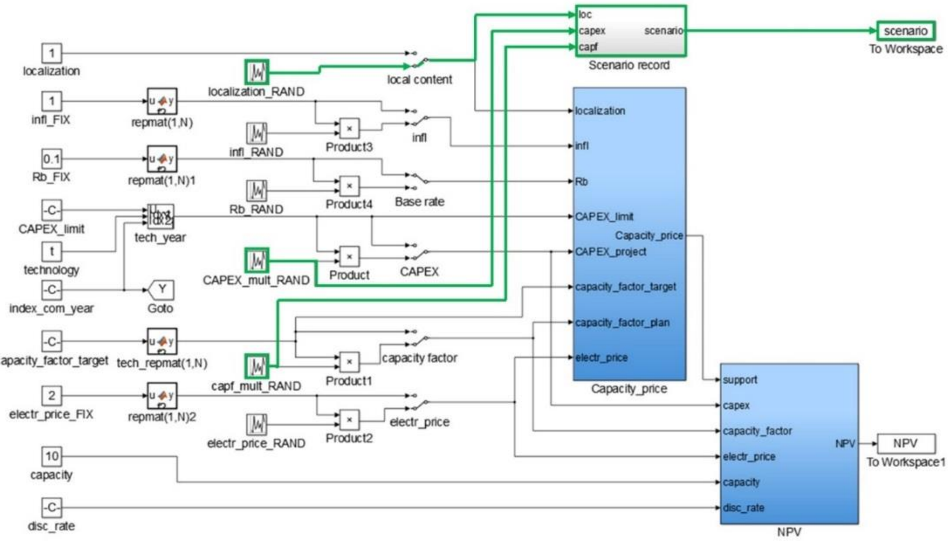

Figure 1. Block-diagram of the used model

3.1. SIMULATION DECOMPOSITION FOR THE CASE IN AN ALGORITHMIC FORM

First step is the identification of the (uncertain) key variables and the possible range of values each key variable can take. The identified key variables are five:

$\tilde{V}=\{\tilde{V}_1,\tilde{V}_2,\tilde{V}_3,\tilde{V}_4,\tilde{V}_5\}=$
=\{Capacity factor, Localization, CapEx level, CPI, Electricity price\}

and the possible range of each key variable´s value is presented in Table 1. For the purposes of this paper the ranges from within which the random draws are made are modeled as uniform distributions (probability is the same for drawing any value from within the range).

The second step is to identify the key variables the organization can affect and to identify relevant states for these variables. The first two factors in Table 1, electricity price and inflation, represent external or “market” factors that are outside the influence of the investor, whereas the remaining three variables represent project-internal factors that can be managed to some extent by project managers: { Capacity factor, Localization, CapEx level}. The relevant states to be studied for each of these three key variables are:

Capacity factor=$\{\tilde{A}_{11},\tilde{A}_{12},\tilde{A}_{13}\}$={Low, Medium, High}

Localization=$\{\widetilde{A}_{21},\widetilde{A}_{22}\}$={Failed, Fulfilled}

CapEx level=$\{\widetilde{A}_{31},\widetilde{A}_{32}\}$={within the limit, over the limit}

Table 1. Uncertain key variables for the RE investment

Key variable	Possible range of values	
	Minimum	Maximum
Electricity price, rub./MWh	1000	3000
Consumer price index CPI (inflation)	1.00	1.70
Capital expenses (CapEx) level	80%	150%
Capacity factor (percent of target)	30%	120%
Localization requirement	Failed (0)	Fulfilled (1)

Thus we have one three-state variable and two binary variables. The identified “states” directly and realistically reflect the features of the Russian RE investment incentive mechanism. The level of the capital expenditures, the level of annual electricity production (capacity factor), and fulfilling a requirement for local production in the investment (localization) affect the amount of support that the investment can receive in the form of RE capacity payments. For example, failing the localization requirement will cut the received RE capacity payments to roughly a half of the maximum. Details of the Russian RE incentive mechanism and the effect of the three variables can be found, e.g., in (Government of Russian Federation, 2013a; Government of Russian Federation, 2013b; Kozlova and Collan, 2016; Kozlova, 2015).

The third step is to identify what was called “suitable boundaries” for the identified states. This means setting, in this case numerical, thresholds $\tilde{t}_{ij}$ that separate the different states, while observing the bounds of each state. Here these thresholds are given by the underlying Russian RE incentive mechanism: for “Capacity factor” we have two threshold values $\tilde{t}_{11}$=50% and $\tilde{t}_{12}$=75% and the boundaries of the three resulting states become $\widetilde{B}_{11}$=[30%,50%], $\widetilde{B}_{12}$=(50%,75%], and $\widetilde{B}_{13}$=[75%,120%], where the minimum and the maximum we get from the range of possible values, see Table 1. Similarly for the binary variable “Localization” we have $\widetilde{B}_{21}$=0 and $\widetilde{B}_{22}$=1 and for “CapEx level” $\widetilde{B}_{31}$=[80%,100%] and $\widetilde{B}_{32}$=(100%,150%].

The fourth step is to form groups $\widetilde{G}_k$ from a list of “combinations of states” between different variables, these combinations will be the to-be-decomposed parts of the simulation. The combinations of states can also be called “scenarios” as denoted in block-diagram in Figure 1.

Simulation results for each round are matched to these scenarios. In this particular case we get 12 scenarios that are listed in Table 2.

Table 2. List of different scenarios with states of the variables identified and boundaries indicated

Scenario, $\widetilde{G}$	Capacity factor (percent of target)	Localization	CapEx level
1	High (75%, 120%]	Fulfilled	Within the limit [80%, 100%]
2	High (75%, 120%]	Fulfilled	Over the limit (100%, 150%]
3	High (75%, 120%]	Failed	Within the limit [80%, 100%]
4	High (75%, 120%]	Failed	Over the limit (100%, 150%]
5	Medium (50%, 75%]	Fulfilled	Within the limit [80%, 100%]
6	Medium (50%, 75%]	Fulfilled	Over the limit (100%, 150%]
7	Medium (50%, 75%]	Failed	Within the limit [80%, 100%]
8	Medium (50%, 75%]	Failed	Over the limit (100%, 150%]
9	Low (30%, 50%]	Fulfilled	Within the limit [80%, 100%]
10	Low (30%, 50%]	Fulfilled	Over the limit (100%, 150%]
11	Low (30%, 50%]	Failed	Within the limit [80%, 100%]
12	Low (30%, 50%]	Failed	Over the limit (100%, 150%]

The fifth step is to run the simulation model, while matching the result of each simulation round (the NPV of the RE investment) not only to the results of the "full" simulation, but also specifically to each of the twelve scenarios. Matching is based on the correspondence of the randomly drawn values for the three variables to the particular states identified by the boundaries of the states. For example, if randomly drawn capacity factor is "79%" that matches the state "high", randomly drawn localization "failed", and randomly drawn CapEx level "105%" that matches the state "over the limit", the NPV from this simulation round would be attributed to scenario number four in Table 2. This process will finally create twelve sub-distributions, one for each scenario and the result will be a decomposition of the simulated distribution. The input-recording part of the used model is denoted with green arrows and block borders in Figure 1.

From the resulting NPV values for the project as a whole and for each scenario separately one can build histograms for the results. The parts must equal the whole. Typically, in a real-world analysis situation one would go about to, e.g., calculate descriptive statistics such as expected NPV, real option value, standard deviation of the NPV, et cetera. Next we look at the results from the numerical case illustration.

3.2. SIMULATION RESULTS

Simulation and simulation decomposition results are used to create histograms of the NPV for the whole project and for the twelve scenarios separately. The histogram for the whole project without decomposition is shown in Figure 2 on the left. What can be seen is that the form of the distribution is interesting. The shape of the distribution is caused by the effect of the Russian RE incentive policy. In Figure 2 on the right one can see the twelve scenarios´ distributions inputted in the same picture and highlighted with different colors. Bars of different scenarios do not overlap in the histogram, but are “summed up” for each NPV value bin. What can be intuitively understood is “where” in the total distribution each scenario is present and what kind of initial values lead to which kinds of NPV results. Expected NPV and real option value (ROV in Figure 2) are indicated for both to highlight the fact that they are (and should be) the same, because both graphical presentations represent the same simulated NPV outcomes.

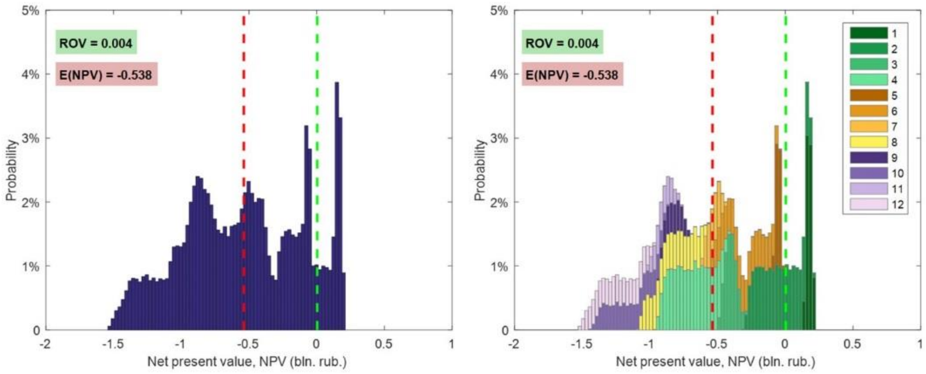

Figure 2. Simulated net present value (NPV) distributions. For legend key, see Table 2

Breaking down the overall simulation results into outcomes of different scenarios provides more information for decision-making. In particular, from the right graph of Figure 2 one can immediately see that the first scenario NPV’s are entirely in the positive zone. This implies that an investor, who is able to manage the key variables to end up in the first scenario can benefit from profitability of a “secure” project and from an independence from volatile market conditions. Also information about the sensitivity of the project profitability to the values of the key variables can be easily read from the decomposed histogram in a way that is not possible by just looking at a “conventional” histogram.

Table 3 presents a selection of calculated descriptive statistics from the results for the whole distribution and for each sub-distribution separately.

For this investment the only sub-distribution that lies entirely in the “positive zone” is that of the first scenario. Notice that also a part of the second scenario distribution is positive. In this case the difference is caused by the CapEx level (see Table 2) and further study shows that to be positive the project should fulfill the localization requirement, keep high average capacity factor, and make sure that the CapEx level is not higher than 120% of the limit. Figure 3 shows histograms of each sub-distribution separately with Expected NPV and ROV values.

Table 3. Descriptive statistics

	Expected NPV	ROV	Standard deviation	Minimum	Maximum	Probability that a simulation result hit the scenario
Total distribution	-538.112	3.888	444.537	-1.543.126	211.925	100%
Scenario 1	163.426	163.426	18.153	123.772	211.925	7%
Scenario 2	-58.143	22.629	133.644	-325.310	205.211	18%
Scenario 3	-414.466	0	42.643	-519.048	-284.235	7%
Scenario 4	-701.176	0	135.105	-971.933	-404.229	18%
Scenario 5	-65.746	0	13.302	-110.960	-30.473	4%
Scenario 6	-308.654	0	135.064	-577.623	-56.636	10%
Scenario 7	-544.211	0	40.795	-635.715	-439.060	4%
Scenario 8	-842.300	0	134.252	-1.105.438	-565.459	10%
Scenario 9	-834.610	0	54.708	-966.813	-689.509	3%
Scenario 10	-1.164.512	0	143.629	-1.453.132	-867.893	8%
Scenario 11	-916.016	0	58.886	-1.056.890	-766.296	3%
Scenario 12	-1.254.252	0	143.134	-1.543.126	-952.481	8%

We also ran a two-sample Kolmogorov-Smirnov test of the resulting sub-distributions. This was done to make sure that our managerial decisions for different states and relevant scenarios was done in a way that was meaningful for the decision making process. This test confirmed that the samples are not drawn from same distribution when comparing the scenarios and further confirming our scenario selection.

The decision-making implications for this case can be shortly summarized by saying that even if the investment does not look very promising, when the whole distribution is looked at, the management can draw the further conclusion that if it is possible to fulfill the localization requirement, keep high average capacity factor, and make sure that the CapEx level is not higher than 120% of the limit, then the investment is likely to be profitable. This information gives actionable management information that the management can start analyzing – the question "are the circumstances that lead to profitability that have thus been uncovered within the reach of the organization or not and if they are, then what are the operational steps to reach them?"

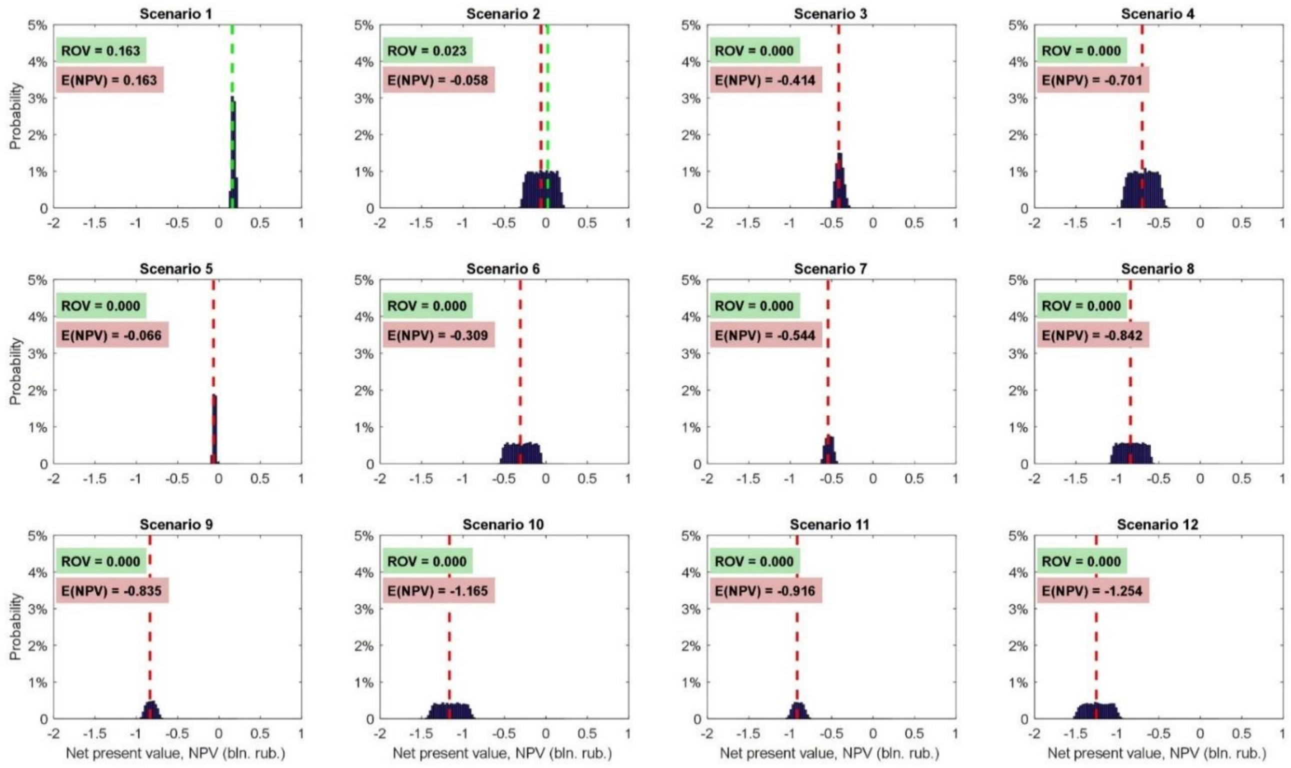

Figure 3. Histograms of each sub-distribution with expected net present values E(NPV) and real option values (ROV)

4. DISCUSSION AND CONCLUSIONS

Simulation-based techniques are commonly used in many fields for the analysis of the joint effects of uncertain variables. One of the fields where simulation techniques have been found useful is investment analysis, where simulations are run based on profitability models built for the studied investments. Typically simulation is used as a tool to create distributions of possible outcomes that are presented in the form of histograms - in this paper we posit that when complex problems, with multiple uncertain and simulated variables, are analyzed it makes sense to decompose the resulting distributions to find out more about the results. For this purpose we present a new method that we have called “simulation decomposition”.

This idea of the method is shortly to create sub-distributions of the overall simulation, by categorizing states of the uncertain variables simulated and by way of forming combinations of different variables´ states and collecting the simulated outputs from each scenario. This way the simulated information is not only used to create a single “overall” distribution from results, but also a number of sub-distributions for the scenarios that the state combinations of the uncertain variables represent. The information that is revealed increases the value of the simulation, because by better understanding the connection between the circumstances (variable states) and the results to which they have lead (simulation results) decision-makers can make better use of the analysis results.

In fact, if the thresholds separating the states of the uncertain variables are such that they represent different levels of effort, or actions such as investments, the information can be formed into actionable “march orders”, for example, in the context of the numerical illustration presented in the paper. The ability to trace the influence of different states of the uncertain factors on the results (project profitability), and the possibility to compare the outcomes of different scenarios and probabilities of different scenarios offer, in our view, enhances decision-support that can be given to managers with simulation.

Using smart graphical presentation and the types of tables and separate scenario distributions will enhance the intuitive understandability of the obtained results. On top of the described benefits the proposed method is rather easy to implement and does not necessarily require any changes to the models that underlie the simulation procedure. The method is also generally usable and is not context dependent.

The numerical case illustration based on a solar PV power plant investment analysis reveals the added analytical insights brought about by the simulation decomposition that can be used to create action points for management of such investments. The method can be used in similar investment analyses, even without such natural thresholds between states of variables that were found in the example used, in such cases the thresholds need to be managerially estimated and decided. Furthermore, the insights uncovered in the numerical case illustration also contribute to the study of the Russian renewable energy policy.

In a broader management decision-support context, the simulation decomposition approach outperforms classical techniques to analyzing sensitivity of the results. It possesses all the features of the traditional simulation and provides more insights on top of the classical simulation practice. The proposed approach reflects some features of sensitivity and scenario analysis that are typically used to complement investment analyses and can also be understood as a more developed approach in the same vein with these methods.

Further research into the topic of distribution decomposition will include studying the real world situation, where managers are asked to identify the thresholds between the different states of the required variables and extending this thinking into investment analysis within the possibilistic framework.

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REFERENCES

AMRAM, M.; KULATILAKA, N. (1998). *Real options: Managing strategic investment in an uncertain world.* Oxford University Press.

BASTIAN-PINTO, C.; BRANDÃO, L.; ALVES, M.D.L. (2010). "Valuing the switching flexibility of the ethanol-gas flex fuel car". *Annals of Operations Research,* Vol. 176, No. 1, p. 333-348.

BLOCK, S. (2007). "Are “real options” actually used in the real world?". *The Engineering Economist,* Vol. 52, No. 3, p. 255-267.

BOOMSMA, T.K.; MEADE, N.; FLETEN, S. (2012). "Renewable energy investments under different support schemes: A real options approach". *European Journal of Operational Research,* Vol. 220, No. 1, p. 225-237.

BOUTE, A. (2012). "Promoting renewable energy through capacity markets: An analysis of the Russian support scheme". *Energy Policy,* Vol. 46, p. 68-77.

BOYLE, P.P. (1977). "Options: A Monte Carlo approach". *Journal of Financial Economics,* Vol. 4, No. 3, p. 323-338.

DATAR, V.T.; MATHEWS, S.H. (2004). "European real options: An intuitive algorithm for the Black-Scholes formula". *Journal of Applied Finance,* Vol. 14, No. 1, p. 45-51.

GARCÍA-REDONDO, F.; LÓPEZ-VALLEJO, M.; ITUERO, P.; BARRIO, C.L. (2012). "A CAD framework for the characterization and use of memristor models". *Synthesis, Modeling, Analysis and Simulation Methods and Applications to Circuit Design (SMACD), 2012 International Conference On,* p. 25-28.

GOVERNMENT OF RUSSIAN FEDERATION. (2013a). 28 may 2013 Decree #449 on the Mechanism of Promoting the use of Renewable Energy in the Wholesale Market of Electric Energy and Power.

GOVERNMENT OF RUSSIAN FEDERATION. (2013b). 28 may 2013 Resolution #861-R on Amendments being made to Resolution #1-R 8.01.2009 on the Main Directions for the State Policy to Improve the Energy Efficiency of the Electricity Sector on the Basis of Renewable Energy Sources for the Period Up to 2020.

GRAHAM, J.R.; HARVEY, C.R. (2001). "The theory and practice of corporate finance: Evidence from the field". *Journal of Financial Economics,* Vol. 60, No. 2–3, p. 187-243.

INTERNATIONAL FINANCE CORPORATION (2011). *Renewable energy policy in Russia: Waking the green giant.* (Retrieved September 2015), available at http://www.ifc.org/wps/wcm/connect/6239e00040c80fcdb865bd5d948a4a50/Green+Giant_Eng.pdf?MOD=AJPERES

JAIMUNGAL, S.; LAWRYSHYN, Y. (2015). "Incorporating managerial information into real option valuation", in: Aïd, R.; Ludkovski, M.; Sircar, R. (ed). *Commodities, energy and environmental finance,* p. 213-238. Springer.

JOHNSON, S.; TAYLOR, T.; FORD, D. (2006). "Using system dynamics to extend real options use: Insights from the oil & gas industry". *International System Dynamics Conference,* p. 23-27.

KOZLOVA, M. (2015) *Analyzing the effects of the new renewable energy policy in Russia on investments into wind, solar and small hydro power*. Master's thesis, Lappeenranta University of Technology, p. 104.

KOZLOVA, M.; COLLAN, M. (2016). "Modeling the effects of the new Russian capacity mechanism on renewable energy investments". *Energy Policy,* Vol. 95, p. 350-360.

KOZLOVA, M.; COLLAN, M.; LUUKKA, P. (2015). "Comparing Datar-Mathews and fuzzy pay-off approaches to real option valuation". *Real Option Workshop,* Lappeenranta, Finland. p. 29-34.

MATHEWS, S.; DATAR, V.; JOHNSON, B. (2007). "A practical method for valuing real options: The Boeing approach". *Journal of Applied Corporate Finance,* Vol. 19, No. 2, p. 95-104.

MONJAS-BARROSO, M.; BALIBREA-INIESTA, J. (2013). "Valuation of projects for power generation with renewable energy: A comparative study based on real regulatory options". *Energy Policy,* Vol. 55, p. 335-352.

MOONEY, C.Z. (1997). *Monte Carlo simulation.* Sage Publications.

NEMBHARD, H.B.; SHI, L.; AKTAN, M. (2003). "A real options design for product outsourcing". *The Engineering Economist,* Vol. 48, No. 3, p. 199-217.

O'REGAN, B.; MOLES, R. (2001). "A system dynamics model of mining industry investment decisions within the context of environmental policy". *Journal of Environmental Planning and Management,* Vol. 44, No. 2, p. 245-262.

O'REGAN, B.; MOLES, R. (2006). "Using system dynamics to model the interaction between environmental and economic factors in the mining industry". *Journal of Cleaner Production,* Vol. 14, No. 8, p. 689-707.

RANE, S.U.; SHET, T.; SRIDHAR, E.; BHELE, S.; GAIKWAD, V.; AGALE, S., *et al*. (2014). "Interobserver variation is a significant limitation in the diagnosis of burkitt lymphoma". *Indian Journal of Medical and Paediatric Oncology: Official Journal of Indian Society of Medical & Paediatric Oncology,* Vol. 35, No. 1, p. 44.

REUTER, W.H.; FUSS, S.; SZOLGAYOVÁ, J.; OBERSTEINER, M. (2012). "Investment in wind power and pumped storage in a real options model". *Renewable and Sustainable Energy Reviews,* Vol. 16, No. 4, p. 2242-2248.

RIDLEHOOVER, J. (2004). "Applying Monte Carlo simulation and risk analysis to the facility location problem". *The Engineering Economist,* Vol. 49, No. 3, p. 237-252.

RYAN, P.A.; RYAN, G.P. (2002). "Capital budgeting practices of the fortune 1000: How have things changed". *Journal of Business and Management,* Vol. 8, No. 4, p. 355-364.

SAVOLAINEN, J.; COLLAN, M.; LUUKKA, P. (2016). "Analyzing operational real options in metal mining investments with a system dynamic model". *The Engineering Economist,* forthcoming.

SHEEL, A. (1995). "Monte Carlo simulations and scenario analysis — decision-making tools for hoteliers". *The Cornell Hotel and Restaurant Administration Quarterly,* Vol. 36, No. 5, p. 18-26.

SONTAMINO, P.; DREBENSTEDT, C. (2014). "A prototype decision making tool of coal mine planning using system dynamics model", in: Drebenstedt, C.; Singhal, R. (ed). *Mine planning and equipment selection,* p. 1475-1484. Springer International Publishing.

TAN, B.; ANDERSON, E.G.; DYER, J.S.; PARKER, G.G. (2010). "Evaluating system dynamics models of risky projects using decision trees: Alternative energy projects as an illustrative example". *System Dynamics Review,* Vol. 26, No. 1, p. 1-17.

TRIGEORGIS, L. (1995). *Real options: An overview.* Praeger Westport, CT.

VASILEVA, E.; VILJAINEN, S.; SULAMAA, P.; KULESHOV, D. (2015). "RES support in Russia: Impact on capacity and electricity market prices". *Renewable Energy,* Vol. 76, p. 82-90.

VITHAYASRICHAREON, P.; MACGILL, I.F. (2012). "A Monte Carlo based decision-support tool for assessing generation portfolios in future carbon constrained electricity industries". *Energy Policy,* Vol. 41, p. 374-392.

YANG, M.; NGUYEN, F.; DE T'SERCLAES, P.; BUCHNER, B. (2010). "Wind farm investment risks under uncertain CDM benefit in China". *Energy Policy,* Vol. 38, No. 3, p. 1436-1447.

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