Energy Policy and Development Centre (KEPA)
National and Kapodistrian University of Athens (NKUA)

Центр Энергетической Политики и Развития
Национального и Каподистрианского Университета Афин

Volume 5, Number 2, July - December 2016
Собрание 5, Номер 2, Июль - Декабрь 2016

Euro-Asian Journal of sustainable energy development policy

Евро-Азиатский журнал по политике развития устойчивой энергетики

Athens 2017

Euro - Asian Journal of sustainable energy development policy

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Dear Reader,

The *"Euro-Asian Journal of Sustainable Energy Development Policy"* is the outcome of the established cooperation among scientists from Europe, Black Sea, Caspian Sea and Central Asia.

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The translations of abstracts to Russian language were carried out due to the kind contribution of Prof. Haji Melikov.

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Дорогой читатель,

“Евро-Азиатский журнал по политике развития устойчивой энергетики” является результатом налаженного сотрудничества ученых из Европы, Черного моря, Каспийского моря и Центральной Азии. Он является частью растущего сотрудничества в рамках деятельности сети PROMITHEAS; сеть, которая включает в себя членов из вышеупомянутых областей и остаётся доступной для новых участников, а также спектр её деятельности включает Ежегодную Научную Конференцию, научные награды, совещания по обмену опытом, семинары и совместное участие в научных исследованиях, финансируемых ЕС.

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Наши постоянные усилия - это повышение качества содержания журнала, и с этой целью мы приветствуем ваш вклад.

Переводы тезисов на русский язык были выполнены при любезной помощи профессора Гаджи Меликова.

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Aim and scope

The PROMITHEAS scientific journal titled "***Euro-Asian Journal of Sustainable Energy Development Policy***" is a semi-annual bilingual (English, Russian) publication addressing policy issues on energy and climate change, mainly from the Black Sea, Caspian, Central Asia and S.E. Europe regions. The aim of the publication is to motivate and encourage the scientific and research human potential of these regions to present their research work in the aforementioned areas. Thus, it is expected that the regional scientific potential will be more easily identified and able to be contacted by regional and EU energy policy and environmental stakeholders. Efforts will be made so as the journal contains articles produced through joint efforts among researchers from the regions and the PROMITHEAS network participants.

The scientific journal will also host articles and executive summaries of scientific reports and studies presented during workshops, organized by the PROMITHEAS Network, regarding energy and climate policy issues. The contents of each issue will be determined by the editorial board.

Major articles will cover a comprehensive range of topics such as:

Energy supply and geopolitics;

Strategic energy planning;

Socio-economics of hydrocarbon reserves exploitation;

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Regional Energy Market development;

Emerging hydrogen technologies;

Renewables;

Energy efficiency;

Socio-economics of transcontinental energy corridors;

Climate change (Mitigation, Adaptation);

Energy and Climate Change modelling;

Analysis and implementation of climate policy instruments;

RTD policies and socio-economics for new forms of energy.

Цели и задания

Научный журнал PROMITHEAS под названием ***«Евро-Азиатский журнал по политике развития устойчивой энергетики»*** представляет собой полугодовой и двуязычной (английский, русский) публикацией, которая уделяет основное внимание вопросам политики в области энергетики и изменения климата, в основном для регионов Черного и Каспийского морей, Центральной Азии и Юго-Восточной Европы. Цель публикации - мотивировать и поощрять научно-исследовательский человеческий потенциал этих регионов представить свою исследовательскую работу в вышеупомянутых областях. Таким образом, ожидается, что региональный научный потенциал будет легче идентифицироваться и иметь возможность связаться с региональными и европейскими энергетическими политиками и заинтересованными сторонами в области окружающей среды. Будут предприняты усилия, чтобы журнал содержал статьи, созданные совместными усилиями исследователей из регионов и участников сети PROMITHEAS.

В научном журнале также будут представлены статьи и исполнительные резюме научных докладов и исследований, представленных на семинарах, организованных сетью PROMITHEAS, по вопросам энергетики и климатической политики. Содержание каждой проблемы будет определено редакционной коллегией.

Основные статьи охватывают широкий круг вопросов, таких как:

- Энергоснабжение и геополитика;

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Transition of energy security performances in Japan: historical and scenario analysis

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Abstract

A secure energy supply is important for Japan, but it is becoming difficult due to increasing energy demand in emerging countries. This study aims to understand how the energy security performances have evolved and will improve in the future in Japan by applying three energy security indicators based on the Shannon–Wiener's diversity. Overall, energy security performances improved until the early 2010s. However, the energy security performances declined after 2011 because of the Fukushima nuclear disaster. In the future, energy security performances will improve under the selected four energy scenarios, compared to the historical levels. Comparing the four scenarios, energy security performances will be higher for the scenarios having balanced primary energy structure including nuclear power. Energy security performances, evaluated by three indictors in this study, are mainly affected by diversity of primary energy sources. In addition, import factors are also important to determine the performances.

Keywords

Energy security performance, energy security indicators, Japan, historical and scenario analysis.

1. Introduction

The self-sufficiency rate of energy (including nuclear and renewable energy) was 6% in 2013 in Japan. The country highly depends on fossil fuels – these accounted for more than 80% of energy supply before the Fukushima Daiichi nuclear disaster and at present account for more than 90%. These fossil fuels are mostly imported and mainly come from the Middle East, which has high geopolitical risks. Because energy demands in emerging countries, such as China and India, are increasing and these countries will secure their energy supply, it will be more difficult for Japan to rely on cheap imported fuels in the near future. Thus, producing its own energy sources and reducing dependence on imported energy are essential.

Nuclear power, which is considered semi-domestic energy, has been one of the energy sources that can reduce dependence on fossil fuels. However, the Fukushima nuclear disaster changed the situation, highlighting the safety issues of using nuclear power. Thus, only three nuclear power plants are in commercial operation (as of November 2016).

As an alternative energy source, renewable energy will be one of the most important elements in securing Japan's national energy supply and solving other environmental issues, such as climate change and air pollution. Although multiple national policies were introduced to diffuse renewable energy after the oil shocks in the 1970s, renewable energy other than hydropower accounted for only a small percentage of total primary energy supply. After the introduction of the Feed-in Tariff (FIT), launched in 2012, the share of renewable energy increased more than the historical trend.

In April 2014, the latest version of the Basic Energy Plan, which was developed after the Fukushima nuclear disaster, was endorsed by the government. The purpose of the plan was to completely revise the energy strategy of Japan, particularly reducing dependency on nuclear power, considering the Fukushima nuclear disaster. The plan prioritizes energy security, but also considers economic efficiency and conservation of the environment, all with a strong focus on safety – so called 3E+S.

In transitioning towards a sustainable society, Japan faces many challenges. The main challenges of energy policies can be summarized as follows. In the Basic Energy Plan, no best energy mix is defined. To establish a sustainable society, the plan indicates that the share of renewable energy should be increased. However, no numerical targets exist for renewable energy. In addition, coal-thermal power is still considered an important baseload power. Furthermore, the position of the government regarding nuclear power is not clear. As mentioned above, the plan indicates that nuclear power is an 'important' baseload power source and, at the same time, that dependency on it should be reduced. The energy structure also closely relates to energy security. Since Japan imports most energy resources, energy costs and a stable energy supply may be at risk if Japan continues to rely on imported fossil fuels.

In July 2015, the Long-term Prospect of Supply and Demand of Energy, which targets year 2030, was released. This prospect was developed based on the aforementioned Basic Energy Plan. According to the prospect, Japan will increase the share of renewable energy to 13-14% of primary energy (22-24% of power generation). In addition, the share of nuclear power will be increased to 10-11% of primary energy (20-22% of power generation). Furthermore, drastic energy saving is expected to reduce energy demand. However, there are still difficulties to resume nuclear power plants and to increase renewable energy to achieve the levels indicated in the prospect.

Many types of research on energy security have been implemented in literature, reviewing different countries and regions, different methods, and different periods. In particular, there is a large number of studies that focus on Asian countries, but few for the case of Japan.

Ren and Sovacool (2015), Wu (2014) and, Yao and Chang (2014) targeted China. Ren and Sovacool (2015) applied an analytic hierarchy process to evaluate energy security with respect to low-carbon energy. Wu (2014) examined China's energy security strategies by focusing on overseas oil investment, strategic petroleum reserves, and unconventional gas development in the 11th and 12th Five-Year Program. Yao and Chang (2014) also used the 4As (availability, affordability, acceptability, and accessibility) approach and evaluated the transition of energy security performance by areas of rhombus made by the 4As in the past (1980-2010). Chuang and Ma (2013) evaluated energy policy in Taiwan using six energy security indicators of four dimensions in the past (1990-2010) and also the future energy policy in terms of energy security using both a modeling approach and the indicators. Shin et al. (2013) analyzed energy security in the Korean gas sector using a model approach (quality function deployment and system dynamics) from the past to the future (1998-2015). Martchamadol and Kumar (2012) evaluated energy security in Thailand from the past to the future (1986-2030). They applied five-dimensional (19 indicators in total) indicators, using statistical data for the historical analysis and a scenario approach for the future analysis. Thangavelu et al. (2015) used an optimization model for exploring a long-term energy mix for society with high energy security and low carbon in the future in Indonesia. Ang et al. (2015a) evaluated historical energy security (1990-2010) in Singapore using 22 indicators of three dimensions. They also conducted scenario analysis for the future (until 2035) based on a business-as-usual projection. Sharifuddin (2014) evaluated energy security in five Southeast Asian countries (Malaysia, Indonesia, Philippines, Thailand, and Vietnam) using 35 indicators representing 13 elements grouped into five aspects of energy security in three periods (2002, 2005, and 2008). Selvakkumaran and Limmeechokchai (2013) evaluated the future energy security (until 2030) with respect to oil security, gas security, and sustainability in three Asian countries (Sri Lanka, Thailand, and Vietnam) using a model approach. Similarly, Matsumoto and Andriosopoulos (2016) used a computable general equilibrium model and an energy security indicator for evaluating the future energy security (until 2050) in three East Asian countries (Japan, China, and Korea) under climate mitigation scenarios. There is also a special issue on Asian energy security from Energy Policy (volume 39 issue 11) in 2011. In the special issue, Takase and Suzuki (2011), using the long-range energy alternatives planning software system, analyzed future energy pathways, which have impact on energy security, in Japan. The authors mainly focus on energy structures in the future under different nuclear power development and greenhouse gas emission abatement.

As shown in the above-mentioned literature, there are many studies on energy security focusing on Asian countries. However, the studies targeting Japan are few, although energy security is an important issue for Japan as mentioned above.

In terms of methodology for evaluating energy security, most studies apply some sort of 'indicators' to statistical data or results of model or scenario analysis. However, different definitions, dimensions, or indexes have been used in each study (see for example Ang et al. (2015b) for a comprehensive review of energy security studies), meaning that there are no consistent definitions or evaluation methods for energy security performance. When evaluating energy security performances of countries, the most important factor is the availability of energy as it is included in the indicators in most of the related studies (Ang et al., 2015b). Furthermore, considering that such indicators are used by policymakers to establish energy policy in a country, a simple and comprehensible methodology is preferable. The Shannon–Wiener index is one of the most common and simple indicators in energy security studies and have often been used in the literature (e.g., Jansen et al., 2004; Grubb et al., 2006; Ranjan and Hughes, 2014; Victor et al., 2014).

The purpose of this study is to evaluate energy security performances in Japan from the past to the future, using comprehensive energy security indicators. For the past, statistical data are used, while for the future, energy scenarios are used. Long-term historical analysis is important to understand what contributes for improving energy security. In addition, the scenario analysis for the future can show how energy mix that is considered under energy policy or scenarios in Japan can (or cannot) contribute to improve energy security.

2. Methods

2.1 Energy security indicators

In order to analyze the historical transition of energy security performances and energy security performances in the future, three energy security indicators are used (Jansen et al., 2004; Lehl, 2009). The proposed indicators enable the analysis of energy (supply) security in the past and the future based on historical data or future scenarios. The first indicator (S1, eq. 1) evaluates the diversity of energy sources based on the Shannon-Wiener index, which is an indicator for evaluating primary energy diversity. Diversity is important for maintaining energy security, because the probability of compensating for the loss of a primary energy source by other energy sources will increase, thus preserving energy security. However, concerning the energy security of countries, it is important to consider where the energy sources come from. In general, domestic energy is safe but a procurement risk exists for imported energy. In addition, similar to diversity of energy sources, diversity of the origin of imported energy contributes in improving energy security. The second indicator (S2, eq. 2) considers the import dependence of the country on its energy sources, as well as its energy imports by origin. In this indicator, all of the energy exporters are treated equally. However, energy security will be worse if energy sources are imported from politically and economically unstable countries. Thus, the third indicator (S3, eq. 6) extends the second one by incorporating a country-risk factor associated with the country's energy imports origins. By definition, the values of three indicators will be S1 ≥ S2 ≥ S3, and they are not comparable.

$$S1 = -\sum_{i=1}^{N} p_i \ln(p_i) \tag{1}$$

$$S2 = -\sum_{i=1}^{N} c2_i p_i \ln(p_i) \tag{2}$$

$$c2_i = \left(1 - dm_i \left(1 - \frac{IM2_i^m}{IM2_i^{max}}\right)\right) \tag{3}$$

$$IM2_i^m = -\sum_{j=1}^{M} m_{ij} \ln\left(m_{ij}\right) \tag{4}$$

$$IM2_i^{max} = -M \frac{1}{M} \ln\left(\frac{1}{M}\right) \tag{5}$$

$$S3 = -\sum_{i=1}^{N} c3_i p_i \ln(p_i) \tag{6}$$

$$c3_i = \left(1 - dm_i \left(1 - \frac{IM3_i^m}{IM3_i^{max}}\right)\right) \tag{7}$$

$$IM3_i^m = -\sum_{j=1}^{M} A_j m_{ij} \ln\left(m_{ij}\right) \tag{8}$$

$$IM3_i^{max} = -M \frac{1}{M} \ln\left(\frac{1}{M}\right) \tag{9}$$

$$A_j = \frac{r_j}{\max_j r_j} \tag{10}$$

where *i*: the types of primary energy, *j*: the origin of primary energy imports, p_i: the share of primary energy *i*, dm_i: the share of imports of primary energy *i*¸ m_{ij}: the share of imports of primary energy *i* from country *j*, r_j: the risk indicator for country *j*, *N*: the number of primary energy types, and *M*: the number of origins of primary energy imports.

2.2 Historical data

To calculate the three indicators for the past (from 1978 to 2014), we obtained the data from the following data sources. First, primary energy production, import, and export in Japan (to calculate the share of primary energy pi and the share of imports of primary energy dmi) are from the Energy Balances of OECD Countries (IEA, 2015b). Since the types of primary energy are broad and in detail in this database, they are aggregated into 10 types of primary energy (i.e., coal, oil, gas, nuclear, hydro, Photovoltaics (PV), wind, geothermal, biomass, and other renewable energy). Primary energy imports by origin (to calculate the share of imports mij) are from the Coal Information (IEA, 2015a), Oil Information (IEA, 2015c), and Natural Gas Information (IEA, 2015d). Finally, the risk indicator is obtained from the World Governance Indicators (World Bank, 2015). Since the original data of the World Governance Indicators range from approximately -2.5 to 2.51, they are normalized to the scale of 0 to 1. The smaller the values, the larger the country risks to secure energy supply.

Among these databases, natural gas imports by origin and risk indicators do not cover the data before 1992 and 1995, respectively. To cover a sufficient time span for the analysis, we complemented the missing data by using the data in the closest existing year (i.e., 1993 and 1996, respectively).

In Japan, total primary energy demand has largely increased from 1960 to the present (Fig. 1). After its peak in early 2000s, the total demand tended to decline. The large increase in the total primary energy demand in 1960s is mainly due to increases in oil demand. However, after the oil shocks in the 1970s, oil demand did not increase, but rather tended to decrease. Until the early 1980s, coal and oil occupied the largest part of primary energy demand, but after that the shares of nuclear and natural gas increased. Hydropower, which is for power generation, was used constantly during the observed periods. The share of other renewable energy sources has increased recently, although these percentages are still small compared to traditional energy sources. After the Fukushima nuclear disaster, the trend has tremendously changed. Because all nuclear power plants were shut down and most of them have not been resumed, the share of nuclear power has been reduced to almost zero. Although total primary energy demand is getting smaller in recent years, such a decline in demand could not compensate for the shut-down of nuclear power plants. This decrease in primary energy supply is compensated for by increases in coal and natural gas. As a result, the share of fossil fuels rose to more than 90%. Although the introduction of renewable energy, particularly PV, has increased after the FIT was implemented in 2012, the share is still very small.

Figure 2 shows how much Japan depends on foreign energy sources. During the observed period, almost 100% of oil was imported. Dependence on imported coal and natural gas was not great from the 1960s to the early-1970s. However, the dependence on imports is rising over time, increasing to almost 100% for these two fossil fuels, similar to oil. These trends show that most of fossil fuels are imported in Japan.

2.3 Scenario analysis

For the scenario analysis for the future, energy scenarios developed by the Institute of Energy Economics, Japan (IEEJ; IEEJ, 2015a, b) are used. These scenarios target the year 2030. As described in Section 1, the Government of Japan released the Long-term Prospect of Supply and Demand of Energy. However, to investigate the broad future possibility, it is suitable to use multiple future scenarios. Therefore, IEEJ's energy scenarios are used in this study.

[1] http://info.worldbank.org/governance/wgi/index.aspx#doc-methodology

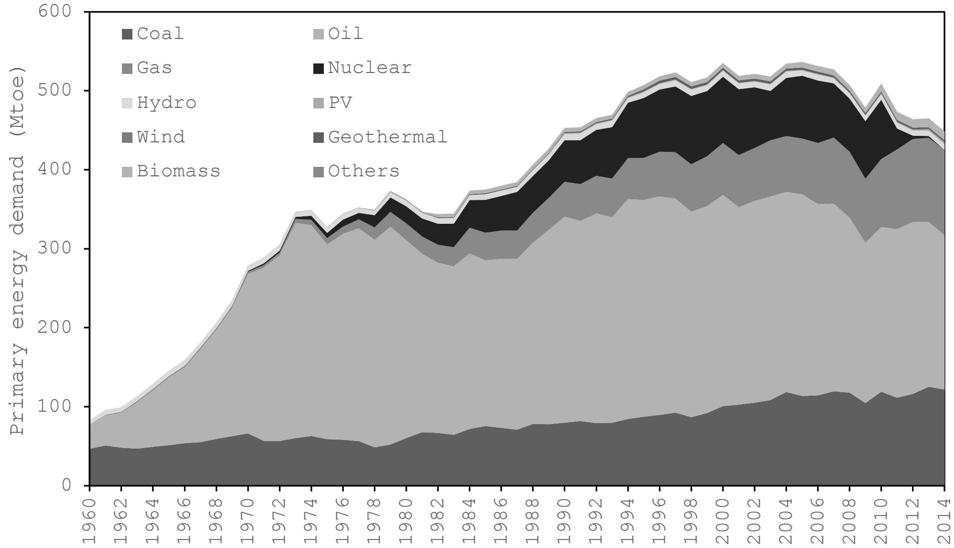

Fig. 1. Structure and transition of primary energy demand. "Others" means other renewable energy. Source: IEA, 2015b.

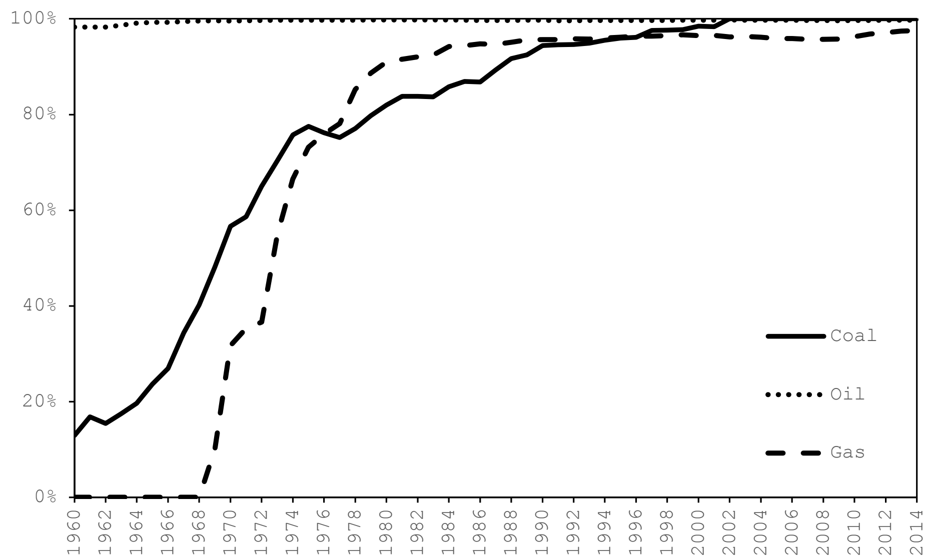

Fig. 2. Dependence on imported fossil fuels. Source: IEA, 2015b.

IEEJ's energy scenarios were developed using their econometric model considering future uncertainties. Four scenarios, hereafter called ES1-4, were developed particularly focusing on the power generation mix (renewable energy and nuclear power). Table 1 shows the overview of the scenarios. The ES1 scenario assumes to use more renewable energy and no nuclear power, while the ES4 scenario uses less renewable energy and more nuclear power. The ES 2 and 3 scenarios are in between the other two. Nuclear power plants meeting the regulatory standards will operate for 40 years in the ES2 scenario, while power plants passing the special inspection extend their operating periods in the ES3 and 4 scenarios. Power generation by renewable energy will be 2.1 to 4.1 times higher than the current level. Since it is not possible to fully replace nuclear power plants, which comprise baseload power, with renewable energy, the share of thermal power is higher in the low-nuclear scenario. Consequently, ES4 shows lower CO_2 emissions and higher GDP than the other scenarios. Figure 3 and Table 2 shows the primary energy structure under the four scenarios.

3. Results and discussion

3.1 Historical trend of energy security performances

Figure 4 shows historical trends of energy security performances evaluated by three indicators. In the early stage of the analysis (from 1978 to early 1980s), all of the three indicators have increased. This is due to a decrease in the share of oil, and an increase in the share of natural gas and nuclear power in the primary energy structure (see also Fig. 1). This trend is brought about by the oil shocks. After the first oil shock in 1973, the government released administrative guidelines to reduce use of oil and electricity. Furthermore, Japan established several policies to secure stable energy supply, such as reduction of dependence on oil and diversification of energy sources by introducing non-fossil fuels, stable supply of oil, energy savings, and research and development of new types of energy. However, the trends are different by indicator after that. The S1 indicator has continuously increased until the early 2010s, while the S2 and S3 indicators (in which energy imports and country risks were taken into account) generally continued to be flat, or become even slightly worse, in the same period.

Table 1. Overview of the IEEJ's energy scenarios.

		ES1	ES2	ES3	ES4
Power generation mix	Renewable energy (%)	35	30	25	20
	Thermal (%)	65	55	50	50
	Nuclear (%)	0	15	25	30
Economy	Power generation (PWh)	1.1	1.2	1.2	1.2
	Power generation costs (JPY/kWh)	21.0	19.0	16.4	14.8
	Real GDP (trillion JPY)	684	690	693	694
Energy	Self-sufficiency ratio (%)	19	25	28	28
Environment	CO_2 emissions (percent change from 2005 level)	-20	-24	-26	-26

Source: IEEJ, 2015a,b

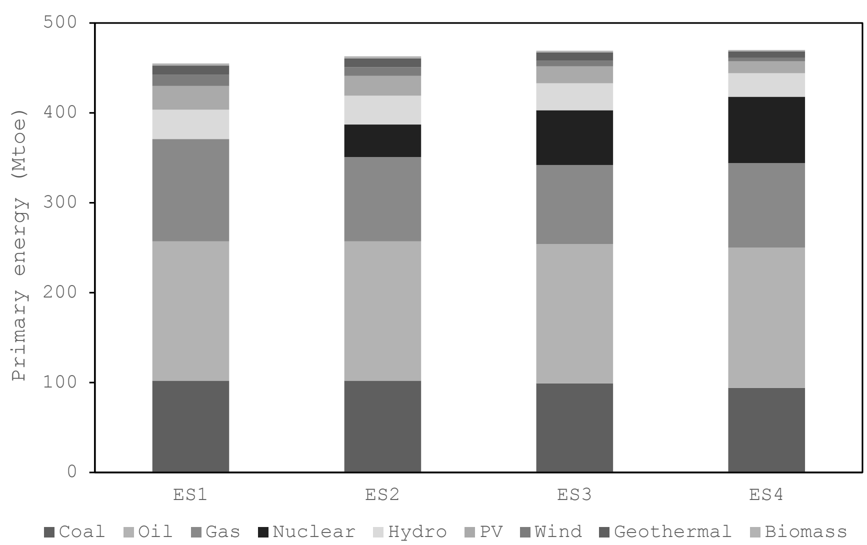

Fig. 3. Primary energy structure under the IEEJ's energy scenarios. Source: IEEJ, 2015a, b.

Table 2 Share of each energy source in primary energy under the IEEJ's energy scenarios.

	ES1	ES2	ES3	ES4
Coal	22.4%	22.0%	21.2%	20.0%
Oil	34.1%	33.5%	33.1%	33.2%
Gas	25.1%	20.3%	18.8%	20.0%
Nuclear	0.0%	7.8%	13.0%	15.7%
Hydro	7.2%	6.9%	6.4%	5.5%
PV	5.8%	4.8%	4.0%	2.8%
Wind	2.8%	2.1%	1.4%	0.8%
Geothermal	2.2%	2.1%	1.9%	1.6%
Biomass	0.5%	0.5%	0.4%	0.3%

Source: IEEJ, 2015a,b

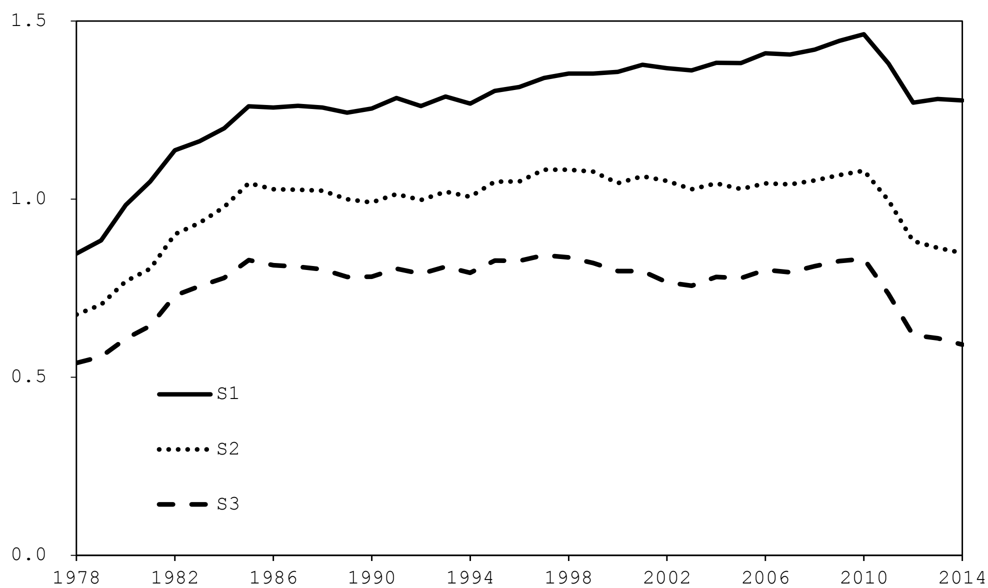

Fig. 4. Historical energy security performances in Japan.

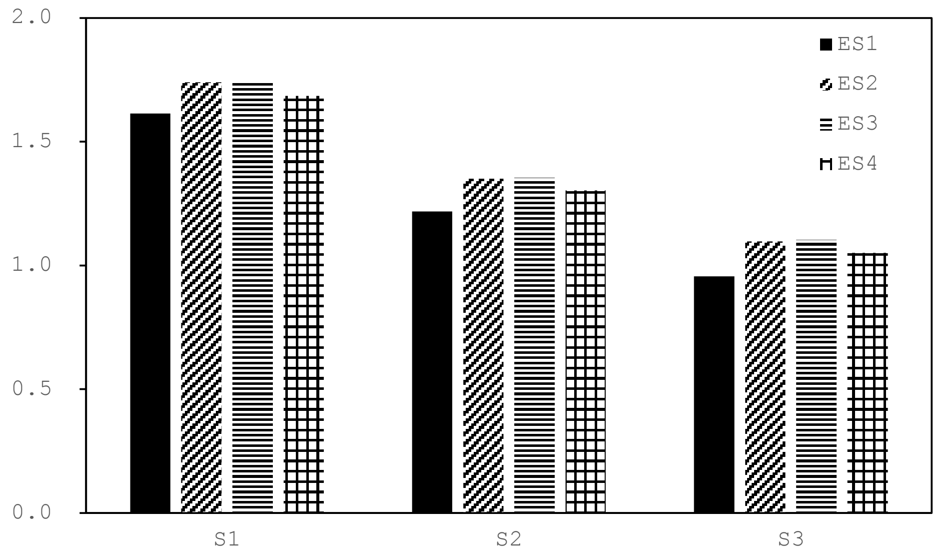

Fig. 5. Future energy security performances under the IEEJ's scenarios.

The S1 indicator purely measures diversity of primary energy. During the corresponding period, the share of oil continuously decreased, while the share of natural gas and nuclear power continuously increased. In addition, the share of renewable energy slightly increased. These effects, in total, increased the diversity of the primary energy sources. In the case of the S2 and S3 indicators, the dependence on imports cause the indicators to be flat from the 1980s to the 2000s. As shown in Fig. 2, the import of natural gas sharply increased until 1980 and slowly but continuously increased after that. The import of coal also increased from 1978 to the present. Such increases in imports offset the increases in value by diversifying energy sources. For the country risk indicator, because same values are used until 1996, country risk affects the energy security indicator only when the share of import by origin changes. If more fossil fuels are imported from higher-risk countries, the energy security performance declines. From 1996, the situation is also similar to that of before 1996 since the country risk indicator does not change greatly. In the case of coal, imports from Australia and Indonesia increased from the mid-1990s to 2000s, while those from Canada and the US decreased. Australia, Canada, and the US are countries with lower risk, while Indonesia is a country with high risk. With regard to oil, imports from Saudi Arabia, which is a higher-risk country, increased, while small decreases were observed in some countries in the same period. For natural gas, imports from Australia, Qatar, and Russia increased, while those from Brunei and Indonesia decreased. Australia is a country with lower risk as indicated above, while Brunei and Qatar are in the middle, and Indonesia and Russia are countries with higher risk. Comparison between the S2 and S3 indicators suggests that import is a more influential factor in determining the performances than the country risk factor.

Finally, after 2010, all three indicators declined tremendously due to the shutdown of nuclear power plants after the Fukushima nuclear disaster. During this period, the decrease in the use of nuclear power was compensated for by fossil fuels, particularly natural gas. This change caused a reduction in the diversity of the primary energy structure.

The above results suggest that the diversity of energy structure is the primary factor in determining the performances of energy security. In addition, imports (total imports and diversity of the origin of imports) are also an important factor. Since the country risk indicator does not seem to affect the performance in this study, it might be due to the fact that the risk indicator changes only slightly over time. Therefore, if an incident, such as a war or a civil war, largely changes the situation of a country, it can affect the energy security performance.

3.2 Comparison of scenarios

In analyzing the scenarios, primary energy sources in the original references were aggregated into the sources treated in the historical analysis, although the scenarios do not include the “others” (other renewable energy). Because the share of “others” is very small, this difference does not affect the comparison between the historical and scenario analysis. Note that since only primary energy structure is available from the references, historical data are applied for energy imports and country risk indicators.

When calculating the S2 indicator for the scenarios, we assume that fossil fuel production in the latest year is kept in the future (to calculate the coefficient c2i). This means that fossil fuel production does not change in 2030 from the current level (production of the 10-year average is used) and the fossil fuel demand that cannot be fulfilled by the production is imported. Similar to the S2 indicator, this assumption on the coefficient (c3i) is also considered for calculating the S3 indicator.

Figure 5 shows the results under the IEEJ’s energy scenarios. Since the same assumption is applied for imports and country risk indicators for all the scenarios, the differences by scenario are similar for each indicator. The results suggest that ES2 and ES3 scenarios show the highest energy security performances (the second scenario is slightly higher than the third one for the S1 indicator, while the third one is slightly higher than the second one for the other two indicators), while the ES1 is the lowest. As Table 1 and Fig. 3 showed, the ES1 is the extreme scenario, which uses no nuclear power at all. It means that the primary energy structure is biased towards fossil fuels, although the share of renewable energy is larger than in the other scenarios. The ES2 and ES3 have more balanced primary energy structures, particularly for important energy sources (energy sources with larger shares), compared to the other two. The ES4 also looks to have balanced energy structure, but the large share of nuclear power reduces the share of renewable energy that consists of several energy types. Consequently, the ES2 and ES3 scenarios have more diversified primary energy structures than the ES4. Observing the S2 and S3 indicators, because import and country risk factors affect evaluation against fossil fuels, the scenarios with higher shares of fossil fuels tend to be more greatly affected.

Comparing the above results with the historical analysis shows that the values in the four scenarios are higher than those in the historical analysis for all the indicators, meaning that the energy security performances are expected to improve in the future under the given energy scenarios. For the three scenarios using nuclear power (ES2-4), use of nuclear power as well as increase in renewable energy contributes to improving energy security performances. Comparing the primary energy structure in this scenario (Fig. 3) with the historical one (Fig. 1) shows that the decrease in nuclear power is compensated for by greater use of renewable energies. In addition, although the total share of fossil fuels remains almost the same, the structure is more balanced by using more natural gas and less oil.

4. Conclusion

Because Japan is poor in energy sources and because its energy situation will be severer in the future, securing its energy supply will be a more significant issue. In this paper, we first evaluated transition in the historical energy security performances and then analyzed energy security in the future under four energy scenarios.

From the historical analysis, it was shown that energy security performances evaluated by three energy security indicators improved over time, although the indicators S2 and S3 were almost flat from the late 1980s to the early 2010s. However, energy security performances declined from 2011 due to the Fukushima nuclear disaster. This means that diversity of primary energy sources, including nuclear power, is important for keeping high energy security performances. From the scenario analysis, energy security will improve under the future scenarios considered in this study. It is suggested that energy balances mentioned above and also energy saving can improve the energy security performances of Japan compared to the historical situation.

To further improve energy security, additional measures can be considered. First, an increase in the share of renewable energy is necessary to balance primary energy structure. This will also decrease dependence on imported fossil fuels. However, if the share of unstable renewable energy increases too much, power system stability will be affected. Therefore, increases of stable renewable sources (e.g., medium- and small-hydro, biomass, and geothermal power) are expected. In addition, introducing energy storage systems will reduce the influence of increasing unstable renewable energy, although such storage systems will generate an additional cost. Next, with regard to energy imports, balancing the origin of imported energy and reducing imports from high-risk countries will also contribute to improvements in energy security, although these affect only the indicators S2 (only the former) and S3. Last but not least, reducing energy demand, i.e., energy saving, is also an important factor for improving energy security performances. By reducing energy demand, energy supply from fossil fuels can be reduced. This will contribute to balancing primary energy sources (increasing the share of renewable energy sources), balancing the origin of energy import, and reducing energy imports from high-risk countries.

Acknowledgments

This research was supported by JSPS KAKENHI Grant Number 15K16161 and 15K00669, and MEXT KAKENHI Grant Number 25241030.

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Изменение показателей энергетической безопасности в Японии: исторический и сценарный анализ

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Краткое изложение: Для Японии важное значение имеет безопасное энергоснабжение, но из-за увеличения спроса на энергию в странах с развивающейся экономикой это становится затруднительным. Целью данного исследования является понимание того, как показатели энергетической безопасности развивались и будут улучшаться в будущем в Японии, применяя три показателя энергетической безопасности на основе разнообразия Шеннон-Винера. В целом показатели энергетической безопасности улучшились до начала 2010 года. Тем не менее, показатели энергетической безопасности снизились после 2011 года из-за ядерной катастрофы на Фукусиме. В будущем показатели энергетической безопасности улучшатся в соответствии с выбранными четырьмя энергетическими сценариями по сравнению с историческими уровнями. Сравнивая четыре сценария, показатели энергетической безопасности будут выше для сценариев, имеющих сбалансированную структуру первичной энергии, включая ядерную энергию. Показатели энергетической безопасности, оцененные тремя показателями в этом исследовании, в основном зависят от разнообразия первичных источников энергии. Кроме того, факторы импорта также важны для определения характеристик.

Ключевые слова: показатель энергетической безопасности, индикаторы энергетической безопасности, Япония, исторический и сценарный анализ.

Comparing pumped hydropower storage and battery storage – Applicability and impacts

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Abstract

As the share of intermittent renewable energy generation rises within the German grid, solutions are required to deal with temporary overproduction of electricity as well as shortfalls. Other changes to energy infrastructure and balancing and ancillary service requirements are expected, due to a changing composition of generating capacity. Pumped hydropower storage systems are natural partners of wind and solar power, using excess power to pump water uphill into storage basins and releasing it at times of low renewables output or peak demand. This is a well-proven, reliable technology, which has traditionally always played a role in providing balancing and ancillary services. However, suitable sites are limited in most countries and where they exist, opposition towards new plants is often high, due to the disruption to landscape and bio-habitats. There are recent developments in battery storage technology, which may be better suited to a largely decentralised energy system. Utility scale batteries using Lithium Ion technology are now emerging.

These could potentially be integrated into the existing built environment, sparing virgin landscape. Nevertheless, battery stores cause also environmental impacts, albeit in different impact categories (e.g. use of scarce natural resources). This paper outlines consequences of increasing renewables on the grid as contextual information, taking Germany as an example. Based on a scientific study for a provider of pumped hydropower storage, the paper clarifies initially the role of pumped hydropower storage and utility scale batteries. It compares their respective technical potentials and limitations in providing certain services. In addition, the paper explores environmental impacts of both technologies over their respective life cycles, drawing on Life-Cycle-Assessment-data.

Keywords

Pumped hydropower, utility scale batteries, balancing and ancillary services.

1. Introduction

In the wake of the Fukushima disaster the German federal government decided on an accelerated energy transition, entailing a shut-down of all nuclear power stations by 2022 at the latest and generating at least 80% of power from renewables by 2050 (Decision of German Cabinet, 2011). Conventional power stations currently cover most of the balancing service requirements of the Transmission Systems Operators (TSOs) involved. However, with their share in the electricity market diminishing, they will no longer be available to cover these requirements to the current degree. At the same time, the need for balancing in the widest sense will increase due to the intermittent nature of much of the prospective 80% renewables making up the energy mix, i.e. wind and solar energy. (Völker et al., 2013, p. 91).

Pumped hydropower storage systems complement wind and solar power well. They use excess power to pump water uphill into storage basins and release it at times of low renewables output or peak demand. Where suitable sites are available, locals often oppose new plants fiercely, due to the disruption to landscape and bio-habitats.

At the same time, battery technologies are developing at a fast pace. Utility-scale batteries have recently emerged, now able to provide a range of balancing services. These can be sited on brownfield sites, thus not impacting on the local landscape to the same degree. However, they have particular requirements as to the materials they are made from, how they can be operated and how they are decommissioned at their end of life. Hence the question arises, how the two storage technologies compare, if considering important environmental impacts over the entire life-cycle.

2. Research Question and Methodology

The three questions to be addressed in this paper are:

- Can utility scale batteries provide an adequate substitute for pumped hydropower storage?
- Given their different technical characteristics, how do they have to be sized to be comparable?
- Which technology performs better, if important environmental impacts are considered over the entire life cycle?

As point of departure, the paper examines the need for storage in the energy system of the evolving German energy transition.

In the second step, both technologies have to be matched as closely as possible in terms of their ability to provide balancing and ancillary services. This requires an analysis based on a literature review.

As a third step of analysis environmental impacts over the whole life cycle are calculated using a simplified Life Cycle Assessment (LCA) based on the ecoinvent database version 3 (Werner et al., 2016), but also incorporating real-life data as and where available.

3. The German Energy Landscape and its Balancing Requirements

A share of 32,5% of renewable electricity could be achieved within the German electricity mix in 2015. At times of peak renewable electricity output, such as a sunny day around mid-day, over 80% of energy demand can be met by renewables, while at times of low irradiation and low wind there can be next to none (Agora Energiewende, 2016). The influx of high levels of solar energy in particular into the grid have led to a drop in energy wholesale prices, even leading to negative prices, when total energy supply surpasses demand. Due to this drop in prices and an ill-functioning EU-ETS (Agora Energiewende, 2016), other conventional energy technologies, namely flexible gas turbines can no longer compete, even though they would complement renewables well, due to their ability to modulate (Beck et al., 2013). The only fuels able to compete are CO_2-intensive coal and lignite. This has led to an altogether unsatisfactory development of CO_2 factors rising between 2011 and 2013 to 622g CO_2/kWh (Icha, 2015), though this is now expected to level off. Furthermore, due to the inflexibility of lignite power stations and intermittent renewables, excess electricity has to be exported into neighbouring grids, such as that of the Netherlands, where gas-generation is now also being displaced, as a result of the low, even negative prices for excess electricity (Agora Energiewende, 2016b; Müller, 2013).

There are therefore many reasons for finding a lower carbon solution for balancing out fluctuations in supply as well as demand, such as storage technologies. Indeed, the market for balancing and ancillary services is expected to change, with conventional generating capacity gradually diminishing and increasing renewables imposing strains on energy infrastructure (Deutsche Energie-Agentur, 2014). Storage technologies are playing an increasing role in providing these services, in particular pumped hydropower storage and large scale batteries. Other storage technologies are being researched intensively (Taylor, 2009; Luo et al., 2015), with high hopes for example placed on compressed air storage, even though this technology is still at pilot stage (Völker et al., 2013).

4. Technologies and Data to be Compared

Two electricity storage options shall be compared – a pumped hydropower store and a large scale lithium-ion store. The pumped hydropower store will provide 1 GW of power and a capacity of 9,6 GWH. The sizing of the battery has to be comparable – see section “Definition of Functional Unit and Time Frame“.

Pumped hydropower storage has been in use since the early 20th century. It is a technically well understood, well proven and reliable technology that can be built at large scale, often having several GWh of storage capacity. Total word wide capacity is estimated at 127 GW (7 GW in Germany; Völker et al., 2013), making it the largest scale technology for electricity storage. It can provide large amounts of balancing energy services (Moseley, 2015). Pumped hydropower storage stores mechanical energy and is being used for load balancing within electric power systems. Energy is being stored in the form of the gravitational energy potential of water, which is pumped from a reservoir at lower level to another reservoir at higher altitude, when there is abundant and or cheap energy in the system. At times of high electricity demand, the stored water is released through turbines which produce electric power. Some losses occur in the pumping process making the plant a net consumer of energy (Moseley, 2015; Lowry, 2017).

With emerging battery needs for a vast range of applications, including electric mobility, research and development of battery development is currently a dynamic, swiftly evolving field (Wang, 2015). With efficiencies of over 90% (e.g. Hiremath et al., 2015; Korthauer, 2013), low memory effect and slow aging charging cycles (Stenzel et al., 2015), lithium-ion batteries are the technology of choice for large scale stationary applications (Korthauer, 2013; Younicos AG, 2016). The particular type of Lithium-Ion technology considered here are Lithium-Manganese batteries. Utility-scale batteries have only emerged recently. They consist of a large number of battery units on racks filling large halls (Koj et al., 2014). Large scale battery stores are operated similarly to pumped hydropower energy storage, storing energy at times of high availability and feeding it back into the grid at times of high demand (Sterner et al., 2015a).

The WEMAG utility-scale battery in the city of Schwerin is currently Germany’s largest utility-scale battery with a capacity of 5 MW and able to store 5 MWh. It went online in September 2014.

It mainly provides short term balancing energy and has been subject to a number of studies (Koj et al., 2015; Koj et al., 2014; Stenzel et al., 2015).

With the use of utility-scale batteries being an emerging field, developments can only partially be anticipated. The assumptions of this study would therefore have to be reconsidered, as and when battery technology evolves.

5. Ability to Provide Balancing and Ancillary Services

In order to compare pumped hydropower stores and utility scale battery storage, it has to be established in how far their technical properties allow for them to be employed in comparable applications. Hence this section explores the role and capacity of the two storage technologies with regard to their suitability for providing balancing and ancillary services.

A study of the German Energy Agency (DENA) on balancing and ancillary services was used as a basis for defining the relevant fields of application (Deutsche Energie-Agentur, 2014). Balancing and ancillary services include frequency control, voltage control as well as emergency and restoration services in the case of blackouts or total system break-down.

Based on the German grid development plan of 2013 (also known as "NEP; (Bundesnetzagentur, 2013), the study assumes a scenario with tripled renewable energy capacity compared to 2013, an increase in gas generating capacity, a completed nuclear energy phase-out and a much reduced share of large scale conventional power stations in the mix. The study comes to the conclusion that, regardless of when such a scenario may happen, it would result in an increased need for decentralised energy generators and energy stores to provide for short falls in balancing energy left by reduced capacity and reduced running hours of large conventional power stations. The increasing level of geographic disparity between power generation and consumption poses strains on the extra-high voltage transmission network leading to increasing requirements for reactive power at that level. With limitations on expanding network capacities in line with growing renewable capacity, the need for redispatch services will also increase. The role of pumped hydropower stations as a possible solution is emphasized (Deutsche Energie-Agentur, 2014).

Mainly but not exclusively based on (Beck et al., 2013; Sterner et al. 2015a; Ulbig, 2015; Höflich et al., 2010) an assessment has been made of the ability of the two types of energy storage to provide the various balancing and ancillary services. The definitions between different kinds of balancing services differ between countries, in particular with regards to the time band covered by different levels of balancing (E-BRIDGE CONSULTING and IAEW, 2016). In Germany there is a distinction between instantaneous frequency response, frequency containment reserve (up to 30 s), frequency restoration reserve (FRR, active in 30s, lasts up to 5 min), replacement reserves (RR, active in 5 min) and longer term operating reserves. Beck et al. (2013) state that both batteries and pumped hydropower storage are able to provide the different types of balancing services. They find that pumped hydropower storage is better suited than batteries to frequency response. This is contrasted by Sterner et al. (2015a), who point out the ability of batteries to respond within milliseconds. Beck et al (2013) and Deutsche Energie-Agentur (2014) see batteries as preferable to pumped hydropower storage for frequency containment reserve, whereas pumped hydropower is certainly suitable as well (Höflich et al., 2010). Both batteries and pumped hydropower storage can provide frequency restoration and replacement reserves, but there is agreement that the pumped hydropower storage is the better option (Beck et al., 2013; Höflich et al., 2010). Sterner et al. (2015a), and Höflich et al. (2010) point out that the issue for batteries is their economic viability. Batteries are not suited to balancing longer periods of low wind and sun or even interseasonal balancing and opinions as to the suitability of pumped hydro-power storage are divided. Generally, power-to-gas or power-to-X is referred to for longer term balancing (Agora Energiewende, 2014; Sterner 2015b). However, due to their typically high energy-to-power ratio (E2P) pumped hydropower stores contribute to longterm balancing, providing power for several days, if fully charged. For example the 9,6 GWh store considered here could supply the electricity demand of 50 000 homes for 20 days (based on figures supplied by a German operator of pumped hydropower stations and Lang et al., 2015). It should be remembered in this context that batteries commonly have an E2P of 1:1 (Krüger et al., 2015), (Wandelt et al., 2015). This is partly due to the fact that the suitability of Lithium Ion batteries for longer term storage is constraint by the fact that they self-discharge over time (about 2-3% per months; Electropedia, 2016). It is also partly due to their cost. All in all the sizing of utility scale batteries is based on economic considerations to provide maximum use and hence maximum return through their application in short term balancing service markets.

A further difference lies in the two technologies' suitability for peak-shaving, which, similar to load levelling, reduces peak demand in order to avoid the need for additional capacity to supply peaks (Corson et al., 2014). Energy storage generally provides fast response and emission-free operation. It is hence well suited for this application. Batteries however are constraint by their particular technical properties. A battery has a set cycle life, after which it needs replacing. A cycle equates to one round of charging and discharging to the full storage capacity, but could be made up of many part cycles. Charging or depleting batteries to maximum capacity strains the battery. Part-cycles are preferable and prolong its lifespan (Arcus, 2016). Hence peak-shaving with frequent larger cycles would be damaging to battery-life (Kohler et al., 2010). Battery arrays should also be over-dimensioned in order to allow for operation in the low state of charge zone (TEC-Institut, 2012).

Reactive power is another service provided to date primarily by conventional power stations. Deutsche Energie-Agentur (2014) identified the need to develop and adapt grid connection rules and technologies, especially for larger decentralised generators to provide reactive power. Both storage technologies are able to provide it, too. Furthermore, they are able to provide the following voltage control services: fault-ride-through, voltage management, phase shifting mode and general voltage stabilisation (Höflich et al., 2010; Sterner et al. 2015a; Agricola, 2015). Equally, emergency and restauration services such as black-start capability and decoupling of supply and demand can be provided by both technologies (Höflich et al., 2010; Sterner et al. 2015a), A summary of this analysis has been compiled in Table 1.

In summary it can be said that suitability for both storage technologies is similar enough to allow for a comparison. It must be remembered, however, that they differ in the extent to which they can provide the services. Batteries are particularly well suited to fast response short term balancing requirements (Agora Energiewende, 2014). Larger storage capacities for longer term services are not currently common (Wandelt et al., 2015). Pumped hydropower energy stores on the other hand tend to hold large volumes, have far higher E2P ratios and thus are able to provide longer term services, even bridging prolonged periods of low renewable energy output at times of low sun and at low wind.

It is these longer term services that are expected to be in greater demand as the share of renewable electricity grows (Völker et al., 2013, p. 91). There are also differences in their preferred running modes. On the one hand, modern batteries will last longer if charging and discharging is done incrementally, avoiding maximum charge and depletion. On the other hand, if pumped hydropower power is running on part-load its efficiency is being compromised. However, any storage technology will have to weigh up their technically preferred running mode against grid requirements and related economic impacts. Thus a trade-off has to be made between maximum operating ours and optimum operational loads.

6. Life Cycle Assessment

Having established that the two technologies have comparable functionality in principle, their global life-cycle impacts will be examined. A simplified Life Cycle Assessment (LCA) has been undertaken using the Umberto NXT software, which accesses the database ecoinvent (Wernet et al., 2016). Umberto NXT universal has been chosen due to its flexibility concerning the modelling and modification of life cycle systems in conjunction with using common LCI databases such as ecoinvent or GaBi[2].

An LCA calculates environmental and human health impacts that result from inputs into the necessary processes (materials, energy) and outputs (emissions, waste…) over the whole life cycle of a product, including manufacturing with upstream processes, operation and disposal at end of life. The

[2] Due to the standardization of LCA the use of other software leads to identical results if the same data is considered.

LCA-Method used complies with ISO14040 and ISO14044 (ISO 14040, 2009-11). The impact categories have been selected based on the following considerations:

- The technologies concerned consume a substantial amount of electricity in their operation, as reflected in the indicators “Global Warming Potential” and “Cumulated Energy Demand” (Goedkoop et al., 2013; Hischier et al., 2010).
- Both technologies require large amounts of minerals and metals in their production and construction, as reflected in the indicators “Cumulated Exergy Demand of Minerals and Metals” (Bösch, Hellweg, Huijbregts, & Frischknecht, 2006).

Table 1. Suitability for Balancing and Ancillary Services (based on Beck et al., 2013, p. 112; Sterner et al., 2015a; Ulbig, 2015; Höflich et al., 2010).

	Pumped hydro-electric Storage	**Utility-scale battery**
Frequency Control		
Frequency response reserve	++	+(+)
Frequency containment reserve (up to 30 s)	+	++
Frequency restoration reserve (FRR) (active in 30s, up to 5 min)	++	+
Replacement reserves (RR) (active in 5 min)	++	+
Bridging of periods of low sun and wind	+	-
Interseasonal balancing	(+)	-
Loads that can be turned on	+	+
Loads that can be turned off	+	+
High/ low frequency response (within 10s, increase/ reduction in active power)	+	+
Load balancing at transmission system level	+	-(+)
Voltage Control (keeping voltage in the allowable band, limiting voltage break-down in case of short circuiting)		
Provision of reactive power	++	+
Reactive power services	+	+
Voltage dependant redispatch	++	+
Fault-ride-through	-	+
Voltage management	+	+
Phase shifting mode	+	+
General voltage stabilisation	+	+
Emergency and Restoration (in emergency, blackout and restoration states)		
Black-start capability	+	+
Decoupling of supply and demand	++	+

key: + + very well suitable, + well suitable, (+) only conditionally suitable, - not suitable

- Pumped hydropower stores constitute substantial interventions into the landscape, as reflected in the indicator “Natural Land Transformation” (Goedkoop et al., 2013).
- The indicators “Eutrophication Potential” and “Human Toxicity (carcinogenic)” have been added in order to reflect impacts on human, animal and plant life (Goedkoop et al., 2013).

The definitions of the impact categories will not be given in detail here – the references given for each should be consulted for further information.

7. Definition of Functional Unit and Time Frame

In order to compare the impact of the two options, they have to be sized in a way that allows for comparable functionality in order to define the so-called “functional unit” (quantified performance of a product system for use as a reference unit as defined by ISO 14040).

Bearing in mind the aforementioned differences in typical energy-to-power ratios, the question arises how to size the two technologies with their different technical characteristics and also slightly different ways in operating and deployment. There are a number of approaches to comparability:

- If both systems are to deliver the same amount of power (MW), both are able to serve short term balancing service requirements. However, longer term balancing service provision would have to be excluded from the comparison, as the battery’s lower E2P will only allow it to operate for minutes up to a few hours.
- If both systems are designed with the same storage capacity (MWh), both can provide the same amount of work, thus allowing for longer term balancing service provision. However, this is not in line with typical sizing of battery storage. A battery store with such a high storage capacity would, according to common E2P rules, have a much higher capacity than the pumped hydropower storage, hence would be able to provide short-term balancing services to a far greater extend than assumed for the pumped hydropower storage.
- If sizing the battery so as to generate merely the same annual output (MWh/a) as the pumped hydropower store, the number of annual full charging cycles for the battery is a decisive parameter. A charging cycle would be taken to be equivalent to the useful storage capacity. The required annual output would thus be divided by typical cycles performed by batteries in a balance energy setting (e.g. according to Stenzel et al., 2015). The result would be the dimension of useful storage capacity of the battery. This would result in a smaller size battery than the previous option. Longer balancing services will however have to be excluded from the comparison in this case as well.

Choosing the capacity (MWh) of the battery as determining factor takes into account the pumped hydropower store’s ability to deliver long-term balancing services. As it is these longer term services which will see an increase in demand, this option will be pursued. Consequently, the functional unit for the comparison will be defined as the provision of 9,6 GWh stored energy, that is able to provide the balancing services defined in Table 1.

Therefore the 5 MWh WEMAG-Battery-store in Schwerin has to be scaled up initially by a factor of 1,920 to meet the requirements of 9,6 GWh. It is assumed that the battery may lose 20% of its storage capacity within 20 years (e.g. Wolfs, 2010) due to aging and degradation processes (reflecting its 20-year warrantee Struck & Broichmann, 2015, p. 6).

It therefore has to be over-dimensioned by 10%, over-producing in the beginning by 10% and under-producing towards the end of life time by 10%, also bearing in mind that the individual battery cells would be replaced gradually, as and when necessary.

Hence in order to provide comparable output on average over the course of its life span, the scaling factor is 2,133. It is unlikely that a utility scale battery 2,133 times the size of the installation in Schwerin would be installed in a single location. More likely it would be spread over a number of locations, each installation of comparable size to the original installation in Schwerin. This allows for the scaling up of a suitable building using the same factor as for battery components. Nevertheless, the battery option will be referred to in the singular in the following.

The life-span of pumped hydropower storage ranges in literature from 50-150 years (Bauer et. al, 2007; VISPIRON, 2015). A life-span of 80 years was chosen which is also the time frame over which the two technologies were compared. There is no long-term evidence yet for life spans of utility scale batteries, as this is a recent and continuously evolving technology. However, a life span of 20 years can be found in literature, e.g. (Hiremath et al., 2015) and is in line with the warranty for the WEMAG-Battery in Schwerin. Hence replacement of the battery units every 20 years has been assumed.

8. System Boundaries

Table 2 shows the components that are included for each technology, reflecting data-availability. Items in brackets will only be accounted for in the LCA up to the point of grid connection.

9. Life Cycle Stages

A cradle to grave analysis will be undertaken. It accounts for impacts in upstream processes resulting from raw material extraction, production and all energy requirements throughout the life cycle. Hence the following aspects will be considered:

- Productions stage: Manufacturing and construction including extraction and all processing of raw materials, transportation processes, construction processes, all energy and water requirements, resulting emissions, wastes and waste disposal.
- Use stage: Operation including management, maintenance and replacement measures, in particular replacement of battery units, difference between stored and generated energy due to efficiency losses and internal electricity requirements, assuming current German electricity mix with current direct emissions and upstream processes of power stations, other generating technologies and infrastructure; for the pumped hydropower storage: lubricating oil consumption and Methane developing in reservoirs (Bauer et al., 2007; Treyer, 2015).

Table 2. System boundaries.

	Utility-Scale Battery	**Pumped Hydropower Storage**
Storage medium	battery cells and case	reservoir and water
Built structures	industrial hall [(building services (heating, cooling ventilation)] racks und trays	tunnel penstock, subterranean turbine hall services for turbine hall surge tank, [services for turbine hall: lighting, ventilation etc.]
Technical components:	inverter cabling [partial] battery management system [partial] [switchgear]	pump turbine, cabling [management system] [switchgear]
Point of hand-over to grid	[transformers]	[transformers]

Our basic assumptions

Table 3. Data and Assumptions.

	Pumped Hydropower Storage	Utility-Scale Battery
Storage capacity	9,6 GWh	9,6 GWh
Power rating	1 GW	9,6 GW (E2P = 1:1)
Efficiency	74,96 %	72,5 %
Total losses per MWH generated	0,350 $MWh/MWh_{generated}$	0,379 $MWh/MWh_{generated}$
Life span	80 years	20 years (= current best practice)
Maintenance and replacement cycles	continuous use of lubricating oil major overhaul of pumps, turbines and generators every 25 years	Replacement of battery units every 20 years (no replacements cycles assumed for the building)
Electricity generated per year	1,855 GWh/a (based on an existing installation)	1,855 GWh/a
Full cycles per year	n/a	194
Deterioration of performance	n/a	20 % in 20 years
Main raw materials	steel: 43,6 Mt concrete: 2966 Mt copper: 0,5 Mt	ecoinvent – data for factory building ecoinvent-Data for lithium-manganese battery
Direct use of land	98 ha	400 m^2 (estimated) x scaling factor
Type of land use	greenfield site	ecoinvent-option for „unspecified land“, which assumes 40% greenfield and 60% brownfield
Other Data	electricity use for building services, control and management systems, methane generation in basins as per eco-invent data for hydro-power	electricity use for building services, control and management systems, Energy density of 114 Wh/kg, Low self-discharge rate
Electricity mix	current German electricity mix used over the whole life cycle (in line with common LCA methodology)	

- End-of Life phase: Decommissioning and disposal including dismantling, separation, processing and recycling, treatment and safe disposal of hazardous wastes, final disposal of non-recyclables, related transportation processes, energy consumption and emissions.

10. Input Data Including Critical Data

For the pumped hydropower store data could be obtained from a pumped hydro-power operator in aggregated form. This data is being complemented by data from ecoinvent and from literature. Technical and operating characteristics will be based on real-life data from the operator.

For the utility-scale battery data is being used from the WEMAG-store in Schwerin, as found in literature (Stenzel et al., 2015; Younicos AG, 2016). Data is being checked against ecoinvent data for Lithium–

Manganese batteries. Quantities in particular stem from ecoinvent. The actual efficiency including all operational losses is based on the utility scale battery in Schwerin.

Upstream processes and their impacts, such as for example those relating to the construction of power stations, which provide the electricity for the use stage of the two storage options, are based on ecoinvent-data.

Based on the available data and previously discussed considerations the following input data is to be used for the Life-Cycle Assessment (Table 3).

11. Environmental Impacts

In Fig. 1 the impacts of both technologies are juxtaposed (utility scale battery = 100%). The different colours indicate shares of the different life-cycle stages in the over-all impacts.

For the pumped hydropower store impacts of the end-of-life stage are barely visible. For the utility scale battery, impacts of the end-of-life stage are discernible and impacts from the production stage are larger. This is largely due to the replacement cycles for the battery units every 20 years, which is shown in Fig. 1 (black and white hatched).

Impacts of the operational stage ("use stage") generally dominate those of the production stage in all categories except cumulated exergy demand. Especially the categories, GWP, eutrophication and impacts on human health show only a small contribution of the production stage to over-all impacts. The use stage is largely made up of the impacts of operational energy losses, i.e. the difference of stored energy and released energy. These losses depend on efficiency losses and internal energy demands of the installations. The impacts of this lost energy in turn depend on the impacts of the current German energy mix, its direct emissions from combustion plants and upstream processes (i.e. impacts from constructing power stations and renewables installations and infrastructure).

The comparison shows that the impacts resulting from the use stage are of similar order of magnitude for both options in most categories, which in turn has an equalizing effect on over-all results. This however does not apply to the categories Cumulated Exergy Demand Metals and Cumulated Exergy Demand Minerals. This impact in the use stage is comparatively small. The reason for this is that impacts of the use stage are mainly due to energy generation, as previously explained. Metals and minerals do not play a major role in energy generation (except for impacts in in upstream chains, i.e. the production stage of power plants within the electricity mix). The category natural land transformation is the only category in which impacts of the pumped hydropower store exceed those of the utility scale battery slightly, based on the assumptions stated previously. The short lines on the bars for natural land transformation indicate how much of these impacts relate to the direct land use of the technologies and how much relates to transformation in upstream processes.

Since impacts from electricity losses in the use stage of both technologies outweighs in most categories those in other stages by far and is similar for both technologies, an analysis was undertaken that excludes these (see Fig. 2). The remaining operational impacts result from construction, battery unit replacements, end-of-life and for the pumped hydropower store lubricating oil and methane development in the reservoirs.

The remaining impacts show higher impacts for the utility scale battery in all categories except natural land transformation, even though direct land-use does not differ much. This is a result of the different types of land assumed for the sites – the pumped hydropower store would be built entirely on greenfield land, while utility scale batteries are more likely to be sited on brownfield sites, such as industrial areas and wastelands. Though in some cases they may be sited near large renewables installations such as wind farms or PV-farms on greenfield land.

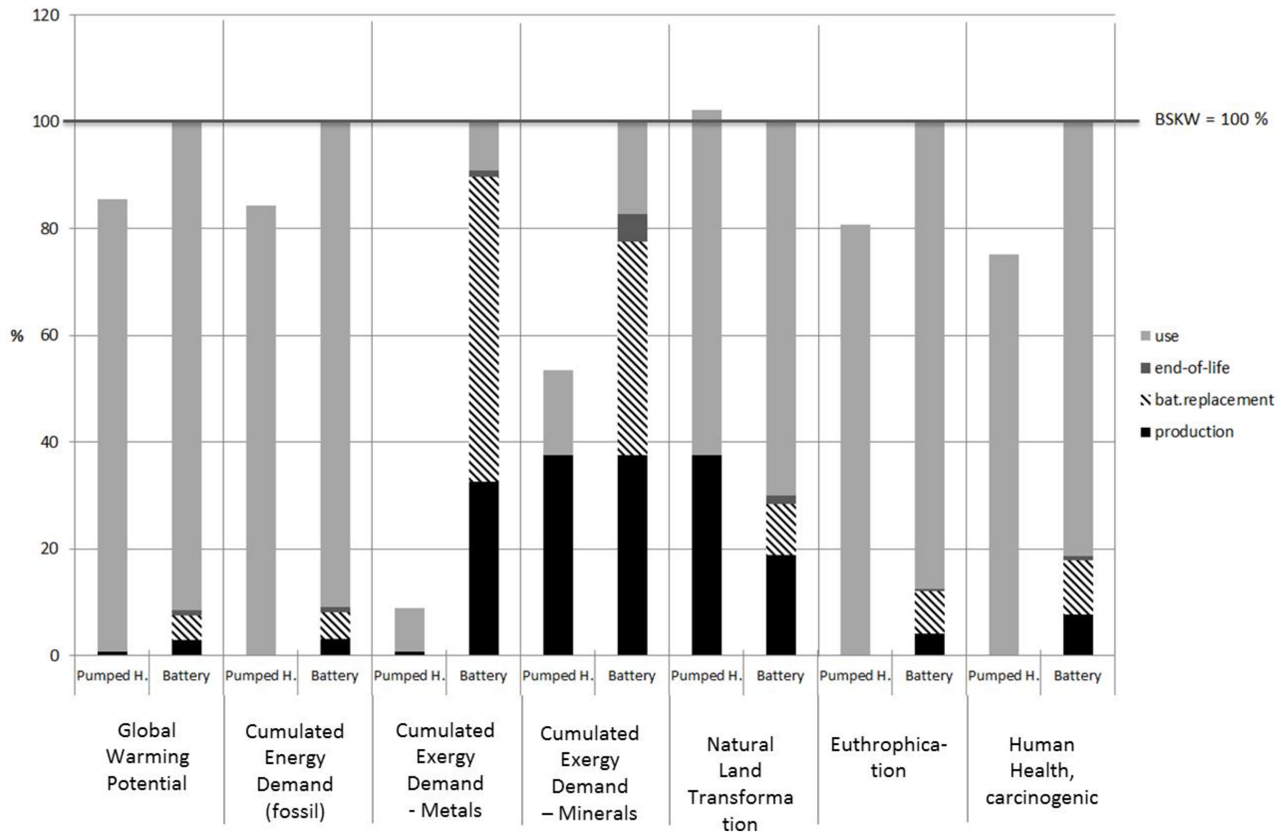

Fig. 1. Comparison of environmental impacts according to life-cycle stage.

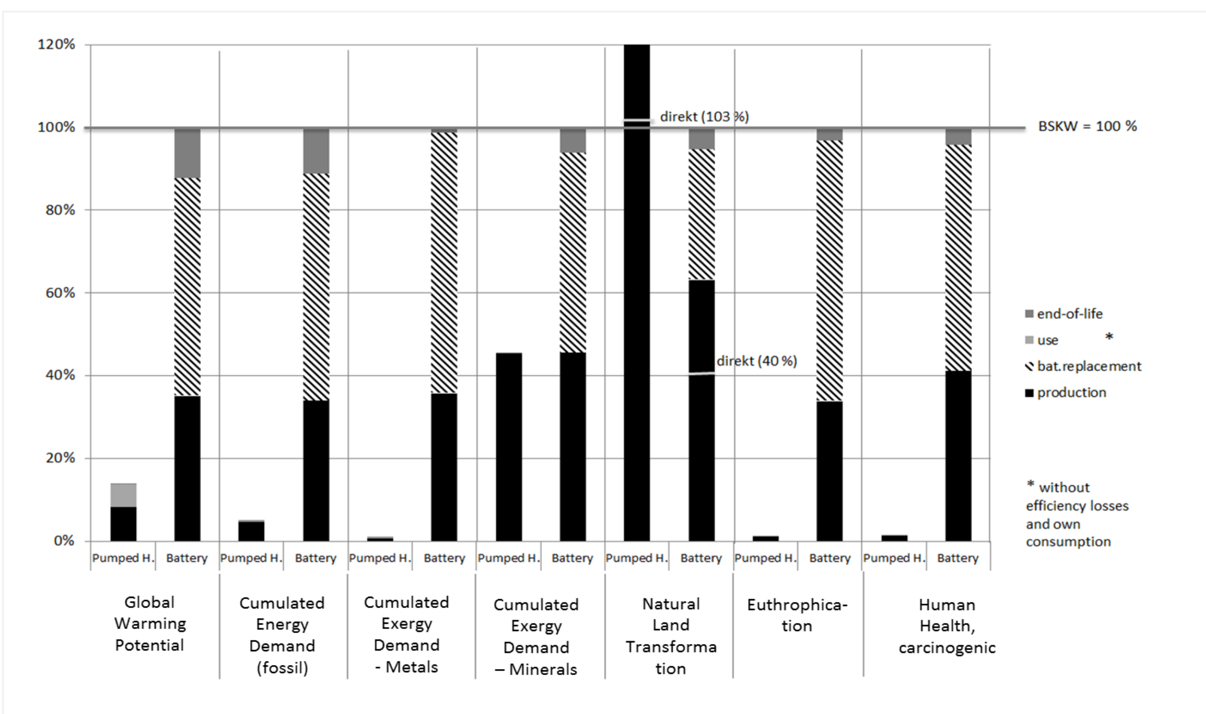

Fig. 2. Comparison of environmental impacts according to life-cycle stage without efficiency losses and internal energy requirements.

12. Discussion of Results

Pumped hydropower stores and utility scale batteries are only conditionally comparable. They can in principle provide the same range of balancing services. However, due to their respective technical characteristics and economic considerations they are deployed differently in practice. Pumped hydropower stores are designed to serve longer term balancing requirements, provide large volumes of energy and can operate at extra-high voltage transmission level. They are also able to bridge periods of low renewable energy output to a certain extend. Utility scale batteries are particularly well suited to short term incremental services and would be part of decentralised generation, usually connected to the distribution system and, due to their different E2P ratios, providing much lower volumes of energy. In so far both technologies can complement each other.

The pumped hydropower store shows lower environmental impacts than the utility scale battery in almost all impact categories, the exception being “natural land transformation”.

Environmental impacts during the use stage dominate the overall result. These depend on the impacts of electricity, which is not fed back due to efficiency losses and internal energy requirements. This means that the system efficiency and internal energy requirement of the examined technologies are crucial for the overall result, as they define electricity ‘lost’ in the 80 year use stage.

High efficiencies of 90-98 % (e.g. Korthauer, 2013) can be found for lithium-ion batteries as opposed to only around 75-80 % for pumped hydropower storage (Beck et al., 2013; Höflich et al., 2010). However, losses for inverters, management system and transformers have to be added, leading to an overall-efficiency of 80-88 % for batteries (VISPIRON, 2015). Furthermore, the utility scale battery has very specific requirements regarding its optimal operational conditions. It requires heating, cooling and ventilation (Santhanagopalan et al., 2014, p. 67). The pumped hydro-electric store requires energy for ventilation and lighting in the underground turbine hall. It furthermore consumes energy for its back-up generator and a number of ancillary services. For both technologies sub-optimal operation at times in response to balancing-requirements have to be assumed. Real-life figures for losses resulting from efficiency losses and internal energy demand have been used and are similar for both technologies. This leads to similar impacts in the use stage for both technologies, which in turn equalise the over-all results of the two technologies. If actual losses of one of the technologies were to change considerably, be it due to technical developments or optimised deployment, this could sway the over-all result in favour of one technology or the other.

Another important parameter to consider is the electricity mix to be used in the LCA-models. It can be treated as a given that the electricity mix will substantially change over the course of the next 80 years, as there are EU-targets and national targets in place, largely relating to emissions reduction leading up to 2050. In an extreme scenario all electricity would come from zero-emission sources and all generating technologies would be produced from recycled materials using zero-emission production energy. In this case emissions arising in the use stage would be negligible. Consequently, the overall result would be similar to that shown in the variation “without efficiency losses and internal energy demand” (Fig. 2). Consequently the equalising effect of the use stage would no longer be there and the percentage of difference between the options over the whole life cycle would no longer be just a few percentage points but be largely amplified. For example, it would be more than ten times larger for the utility scale battery in the category “cumulated energy demand” and around 100 times larger in the category cumulated exergy demand for metals.

However, the energy generation technologies for this extreme scenario do not yet exist. Even current zero-emission electricity generation technologies carry many uncertainties regarding their upstream processes. Modelling these would be an extensive LCA-exercise in itself. Therefore, the current German electricity mix with its currently high emissions and its upstream processes has been assumed for the whole life cycle (as in Fig. 1). This approach is in line with common LCA-conventions.

Whereas the starting point for this study was a specific case study, the only site specific data used where the quantities of materials for the pumped storage (which are rough ball-park figures, as the project has not entered yet specification stage). The methodology of LCA provides aggregated results for global, non-site specific impacts. Within the constraints of the simplifications made (reliance on ecoinvent data - see table 2), the results can be seen as a general, non-site specific comparison of the two technologies.

13. Summary and Conclusions

Pumped hydropower storage and utility scale batteries can provide largely similar balancing and ancillary services, but are only conditionally comparable and are not interchangeable, one for the other.

The pumped hydropower store is typically designed to provide longer term services, including the bridging of longer periods of low sun and simultaneously low wind. The batteries are particularly well suited to short term incremental balancing. Both take part in the short term balancing markets. The demand for balancing and ancillary services is expected to increase.

The utility scale battery has been sized to have the same storage capacity as the pumped hydropower store in order to match it as closely as possible to the pumped hydropower store in terms of the ability to provide the full range of balancing and ancillary services. The implication that, due to different E2P ratio, it could then provide short-term balancing services exceeding those of the pumped hydropower store was neglected for this study.

A simplified LCA has been calculated in order to assess global impacts along the entire life-cycle, calculating the following impacts: Global Warming Potential, Cumulated Exergy Demand Minerals and Metals, Natural Land Transformation, Eutrophication, Human Health (carcinogenic).

The analysis shows lower impacts for the pumped hydropower store in all impact categories except transformation of natural land.

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Сравнение гидроаккумулирующей электростанции и аккумулятора – Применимость и влияние

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Краткое изложение: Поскольку доля выработки электроэнергии периодического действия с использованием источников возобновляемой энергии растет в пределах сети Германии, необходимы решения для вопроса временного перепроизводства электроэнергии, а также ее дефицита. Ожидаются другие изменения в энергетической инфраструктуре, балансировании и вспомогательных услугах из-за изменения состава генерирующей мощности. Гидроаккумулирующие системы являются естественными партнерами ветровой и солнечной энергии, используя избыточную мощность для перекачивания воды в гору в хранилища и выпуская ее в периоды низкой производительности возобновляемых источников энергии или пикового спроса. Это хорошо зарекомендовавшая себя надежная технология, которая традиционно всегда играла роль в обеспечении балансирования и вспомогательных услуг. Однако в большинстве стран ограничено число подходящих участков, и там, где они существуют, наблюдается сильный протест против новых заводов из-за разрушения ландшафтов и среды обитания растений. В последнее время развиваются технологии аккумуляторов, которые лучше подходят для децентрализованной системы энергоснабжения. В настоящее время появляются аккумуляторы для коммунальных предприятий, использующие литий-ионную технологию. Они могут быть потенциально интегрированы в существующую построенную среду, экономный первоначальный пейзаж. Тем не менее, аккумуляторы также вызывают воздействие на окружающую среду, хотя и в разных категориях воздействия (например, использование ограниченных природных ресурсов). В этой статье излагаются последствия увеличения возобновляемых источников энергии в сетке в качестве контекстной информации, взяв в качестве примера Германию.

Основываясь на научном исследовании для поставщика гидроаккумулирующей электростанции, в статье сначала излагается роль гидроаккумулирующей электростанции и аккумуляторов для коммунальных предприятий. Статья сравнивает их соответствующие технические возможности и ограничения в предоставлении определенных услуг. Кроме того, в документе рассматриваются экологические воздействия обеих технологий на их соответствующие жизненные циклы, основанные на данных по оценке жизненного цикла.

Ключевые слова: гидроаккумулирующая электростанция, аккумуляторы для коммунальных предприятий, балансирование и вспомогательные услуги.

Public perception of energy system transformation in Germany

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Abstract

Energy system transformation, also called energy transition, means fundamental structural changes in energy systems. The main objectives of the energy transition in Germany, known as the "Energiewende", are to decarbonize the energy supply by switching to renewable sources and to reduce energy demand by using energy more and more efficiently. This requires, for example, changes in the energy mix, the application of new energy technologies or changes in citizens' demand behaviour. However, such transformation strategies, even if they are technically and economically feasible, may become politically unfeasible if they are not accepted by the public. Therefore, the reliable assessment of public perception is essential for the successful management of transforming the energy system.

The aim of the paper is to explain and illustrate how a tool termed technology monitoring is used in order to assess public perception of the transformation of Germany's energy system. After describing the research questions examined by technology monitoring as well as the elements and methods of the tool, two examples are used to illustrate how technology monitoring can contribute to the assessment of public perception of energy system transformation: CO_2 capture and storage (CCS) and the extraction of shale gas.

For this purpose, the public perception of CCS and shale gas extraction in Germany is first compared along the indicators of self-reported awareness, factual knowledge, risk perceptions, benefit perceptions and general attitudes by applying descriptive statistical analyses.

The results of the descriptive statistical analyses show differences over time in the self-reported awareness about CCS and shale gas. The level of knowledge about both technologies increased over time with regard to some aspects, while it remained stable with regard to others. At the same time, misconceptions about CCS and shale gas extraction among the public exist and persist over time.

The descriptive statistical analyses also revealed that the societal risks of CO_2 storage, CO_2 transport and shale gas are deemed higher than the personal risks and that the societal benefits are perceived to be higher than the personal benefits. The general attitude of the German public is considerably more negative towards shale gas than towards CO_2 pipelines, CO_2 storage and CCS. Furthermore, CO_2 onshore storage is assessed more negatively than CO_2 offshore storage, CO_2 pipelines or CCS.

Four linear regressions were performed in order to identify the determinants of attitudes towards CO_2 pipelines, CO_2 onshore storage, CO_2 offshore storage and the extraction of shale gas. The results show that the most important direct determinants of general attitudes towards CO_2 pipelines, CO_2 onshore storage, CO_2 offshore storage and the extraction of shale gas are the perceptions of personal and societal risks.

In summary, by using the examples of CCS and shale gas extraction the present study shows that technology monitoring contributes to the assessment of public perception of energy system by providing information which can be valuable in order to assess the societal feasibility of future energy systems and delivering information which can facilitate the management of the energy transition.

Keywords

Public perception, energy system transformation, Germany, technology monitoring, CO_2 capture and storage, shale gas extraction.

1. Introduction

Energy system transformation, also called energy transition[3], means fundamental structural changes in energy systems, which have occurred in the past and still occur worldwide (World Energy Council, 2014). However, energy transitions differ in terms of motivation, objectives, drivers and governance [ibid.]. The main objectives of the energy transition in Germany, known as the "Energiewende", are to decarbonize the energy supply by switching to renewable sources and to reduce energy demand by using energy more and more efficiently (Federal Ministry of Economics and Technology (BMWi), 2015). In this way, Germany aims to make a significant contribution towards combating climate change.[4]

The transformation of the existing energy system in Germany into a more sustainable system requires long-term fundamental changes, which include changes in the energy mix, the application of new energy technologies and possibly the exploitation of new energy sources, but also changes in citizens' demand behaviour. However, such transformation strategies, even if they are technically and economically feasible, may become politically unfeasible, if they are not accepted by the public. Therefore, the reliable assessment of public perception is essential for the successful management of transforming the energy system.

The aim of this paper is to explain and illustrate how a tool termed technology monitoring is used in order to assess public perception of Germany's energy system transformation. First, the research questions and the aim of technology monitoring will be described as well as the elements and methods of the tool. Subsequently, by using the examples of CO_2 capture and storage (CCS) and the extraction of shale gas it will be shown how technology monitoring can be used for the assessment of public perception. This will include a comparison of the public perception of CCS and shale gas extraction in Germany along the indicators of self-reported awareness, factual knowledge, risk perceptions, benefit perceptions and general attitudes by applying descriptive statistical analyses. Furthermore, the determinants of attitudes towards CO_2 pipelines, CO_2 onshore storage, CO_2 offshore storage and the extraction of shale gas will be identified by applying regression analysis. Against this background, the contributions of technology monitoring for the assessment of public perception of energy system transformation in

[3] The terms "energy system transformation" and "energy transition" are used synonymously in this paper.

[4] The goals and measures of the energy transition in Germany are described in detail in the German government's Energy Concept and the 10-point energy agenda (Federal Ministry of Economics and Technology (BMWi), 2014, Federal Ministry of Economics and Technology (BMWi) and Federal Ministry for the Environment; Nature Conservation and Nuclear Safety (BMU), 2010).

general as well as possible contributions to energy scenarios in particular will be explained.

Prior to the present article, results of applying technology monitoring were presented by the author at the 8th International Freiberg Conference on IGCC & XtL Technologies in 2016 in Cologne[5] and published in a working paper.[6] However, the presentation for the 8th International Freiberg Conference and the working paper include results regarding the public perception of the usage of coal and coal phase-out in Germany and do not contain any results regarding the public perception of CCS or shale gas. Thus, they deal with subjects which are totally different from the subject of the present paper. The method used in the presentation and the working paper is similar to the method explained in the present article. This is due to the fact, that technology monitoring is a tool which can be used in order to investigate public perception of energy system transformation in Germany including different aspects such as public perception of CCS, shale gas, the usage of coal or coal phase-out. One advantage of applying technology monitoring is, among others, that it makes it easy to compare the public perception of CCS, shale gas or coal phase-out. However, whereas the presentation for the 8th International Freiberg Conference and the working paper focus on the public perception of the usage of coal and coal phase-out, the present paper deals with the public perception of CCS and shale gas.

The first results of a comparison of CCS and shale gas in Germany were presented by the author at the IEA GHG 5th Social Research Network Meeting in 2016 in Cambridge, UK.[7] This event was an internal meeting of the social research network, in which only a small number of network members participated. In the present paper the results of a comparison of CCS and shale gas in Germany are explained in detail and placed in the context of examining the question of how technology monitoring can be used in order to assess public perception of the transformation of Germany's energy system. This was not previously described in an article and has not yet been published.

2. Technology monitoring

Technology monitoring is part of the integrated assessment of energy systems which is the main focus of the interdisciplinary work of the Systems Analysis and Technology Evaluation group at the Institute of Energy and Climate Research of Forschungszentrum Jülich. The integrated assessment of the transformation of energy systems includes a technical, economic, environmental and social assessment. The social assessment of energy system transformation comprises the organization and implementation of stakeholder dialogues, the investigation of mentalities and patterns of behaviour related to energy consumption, life cycle sustainability assessment and technology monitoring. Technology monitoring is the main approach for assessing public perception of energy systems transformation and will be described in more detail in the following sections.

2.1. Research questions and aim of technology monitoring

In order to assess the public perception of the energy transition in Germany, technology monitoring investigates three general research questions: (1) What is the status quo? (2) What dynamics does it have? and (3) What are the determinants?

Investigating the first question includes assessing how aware the general public is of the energy

5 Cf. http://tu-freiberg.de/sites/default/files/media/professur-fuer-energieverfahrenstechnik-und-thermische-rueckstandsbehandlung-16460/publikationen/2016_22-4.pdf

6 http://www.fz-juelich.de/SharedDocs/Downloads/IEK/IEK-STE/DE/Publikationen/preprints/2016/preprint_12_2016.pdf?__blob=publicationFile

7 Cf. http://www.ieaghg.org/docs/General_Docs/5th_SRN/D._SchumannSEC.pdf

transition and what knowledge and attitudes the public has. Examining the second question consists in measuring how public awareness, knowledge and attitudes develop and change over time. Exploring the third question means revealing the relevant factors which determine public perceptions and general attitudes.

Thus, the aim of technology monitoring is to contribute to the assessment of public perception of the transformation of Germany's energy system by surveying the awareness, knowledge and attitudes among the German public regarding technologies, instruments and impacts of the energy transition.

2.2. Methods of technology monitoring

The core element of technology monitoring is a representative survey of the public in order to measure the perception of the transformation of the energy system in Germany. The survey has been carried out annually since 2011/12 (= IEK-STE Panel Survey). The population of the IEK-STE Panel Survey are all German citizens over the age of 18 with a landline connection (cf. Table 1). Participants in the survey were recruited using multi-stage systematic random sampling. For the selection of the respondents, the last birthday selection method is used, i.e. the person above the age of 18 in the household who celebrated their birthday most recently will be interviewed.

Every year (= panel wave) at least 1000 interviews are undertaken. The distributions of socio-demographic characteristics in the sample are compared with the data of the Microcensus, which is a representative household survey carried out by the German Federal Statistical Office.

Every wave of the panel survey comprises questions which are asked every year (= core questions; e.g. questions regarding attitudes towards energy sources) as well as questions on specific topics of current interest (e.g. questions regarding attitudes towards CCS, shale gas or expansion of the electricity grid), which vary every year or which are repeated at greater time intervals (e.g. every two years).

Further essential elements of technology monitoring are specific representative surveys of the German public performed only once in order to investigate research questions related to research projects focusing on specific energy technologies; e.g. CO_2 storage, energy storage, vehicle to grid (Daamen et al., 2011, Dütschke et al., 2014, Dütschke et al., 2015, Pietzner et al., 2011, Pietzner et al., 2014, Schumann et al., 2014, ter Mors et al., 2013) or other aspects of the transformation of the energy system, e.g. energy consumption or energy security.

Table 1. Parameters of the IEK-STE Panel Survey.

Parameter	**Specification**
Population	All German citizens above the age of 18 with a landline connection
Sampling procedure	Multi-stage systematic random selection from existing landline numbers in Germany
Selection of the respondent	Last-birthday selection: person above the age of 18 in the household who most recently celebrated their birthday
Sample size	At least 1000 persons
Criteria for the representativeness of the sample	▪ Gender ▪ Age ▪ Professional qualification ▪ Income ▪ Household size
Database for verifying the representativeness of the sample	Data of the Federal Statistical Office (Microcensus)
Survey method	Computer-assisted telephone interviews (CATI)

Source: authors' own

In the IEK-STE Panel Survey, three main indicators are used to assess the public perception of energy system transformation: self-reported awareness, factual knowledge and attitudes of the citizens. The data are analysed with methods of descriptive statistics (frequencies, means, standard deviations, and correlations), inductive statistics (regressions, hypothesis tests) as well as with more complex multivariate methods of analysis (e.g. structural equation modelling).

In the following, the examples of CO_2 capture and storage (CCS) and the extraction of shale gas will be used in order to illustrate how technology monitoring can contribute to the assessment of public perception of the energy transition.

3. Assessment of public perception of CCS and shale gas in Germany

CO_2 capture and storage (CCS) is perceived worldwide and in the European Union (EU) as a key technology for mitigating greenhouse gas (GHG) emissions (European Commission, 2013, IEA, 2015). Since CCS can be applied for reducing CO_2 emissions from fossil-fuel-based electricity generation it could be used as a strategy for transforming the German energy system into a more sustainable system. Therefore, the analysis of the perception of CCS among the German public is relevant for assessing the public's perception of the transformation of the energy system.

The extraction of shale gas is seen as a strategy for enhancing energy security (IEA, 2012) and could play an important role in transforming the German energy system into a system that employs less oil and is less dependent on oil imports. Thus, the evaluation of the public perception of shale gas extraction in Germany is important for assessing the perception of the energy transition among the public.

In order to assess the perception of CCS and shale gas among the German public, the self-reported awareness, knowledge and attitudes of the citizens were surveyed for the first time in 2011/12 in the first wave of the IEK-STE Panel Survey and for the second time in 2015 in the fourth panel wave. Furthermore, the public perception of CO_2 offshore storage, CO_2 onshore storage and CO_2 pipelines was surveyed in more detail in three representative surveys (a nationwide survey and two regional surveys) of the German public, which were carried out in 2013 within the framework of a project called "CCS Chances" (Dütschke et al., 2015).[8] In this paper, the data of the two panel waves as well as the data of the national "CCS Chances Survey" were used to compare the public perception of CCS and shale gas in Germany along the indicators of self-reported awareness, factual knowledge, risk perceptions, benefit perceptions and general attitudes by applying descriptive statistical analyses. Additionally, linear regression analyses were performed in order to identify the factors that determine general attitudes towards CO_2 pipelines, CO_2 onshore storage, CO_2 offshore storage and the extraction of shale gas.

3.1. Self-reported awareness about CCS, shale gas and fracking over time

Awareness is an indispensable prerequisite for forming or having an attitude towards a person, object or issue. In our surveys, the respondents reported their awareness about CCS, shale gas and fracking by answering the question of whether they had heard about the topics by choosing between the different predefined answers "no, never heard of it", "yes, heard of it, but know nothing or just a little bit about it" or "yes, heard of it and know quite a bit or a lot about it". Accordingly, the results on public awareness in this paper are results concerning "self-reported awareness".

[8] https://www.tib.eu/suchen/download/?tx_tibsearch_search%5Bdocid%5D=TIBKAT%3A835363600&cHash=bfea90dc8a82276cf056479593a0fb61#download-mark (webpage in German).

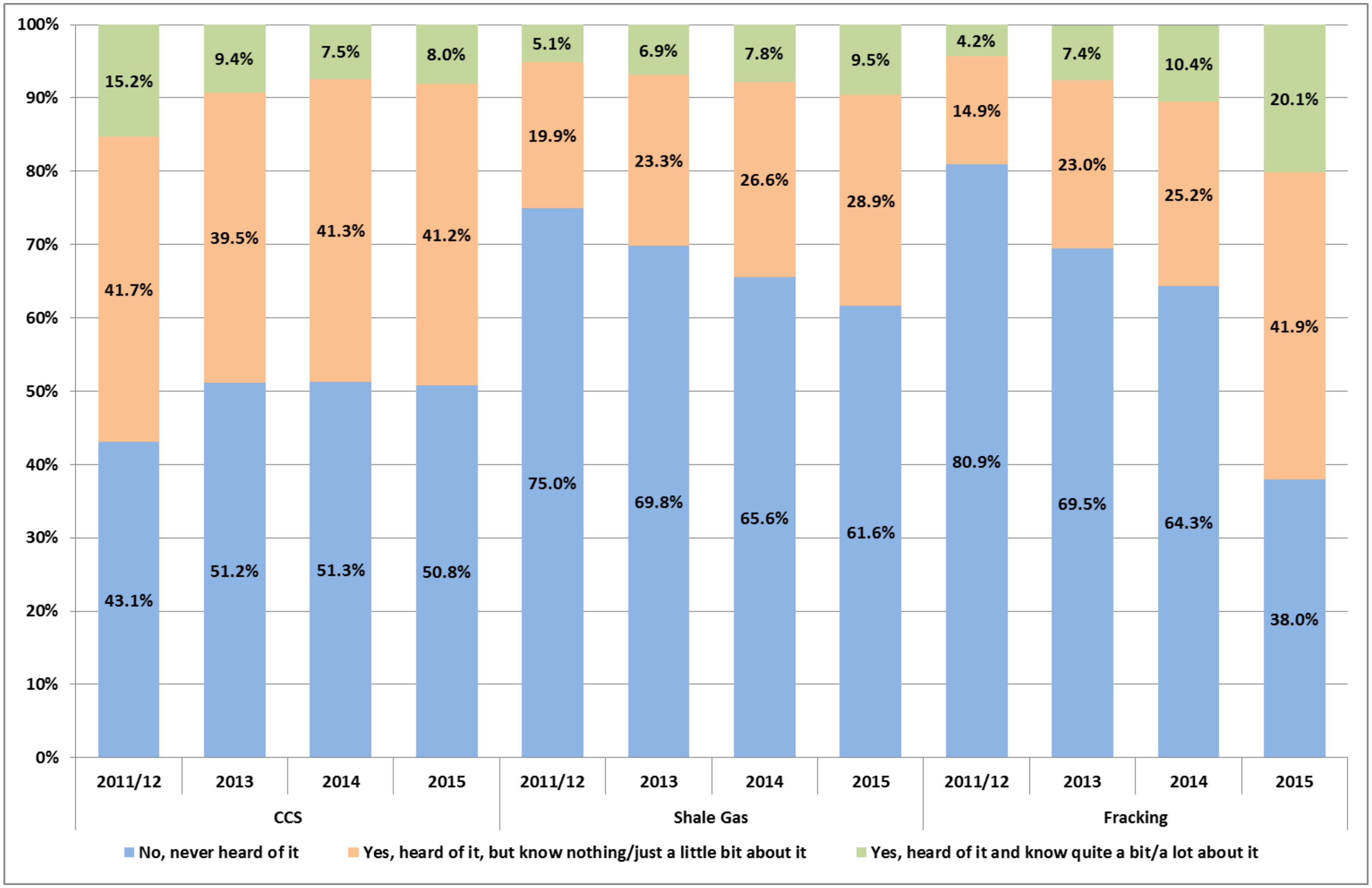

Fig. 1. Self-reported awareness about CCS, shale gas and fracking over time.

Data sources: IEK-STE Panel Survey 2011/12 (n=1000), 2013 (n=1034), 2014 (n=1006), 2015 (n=1000). Question: “Have you heard about the following topics?”

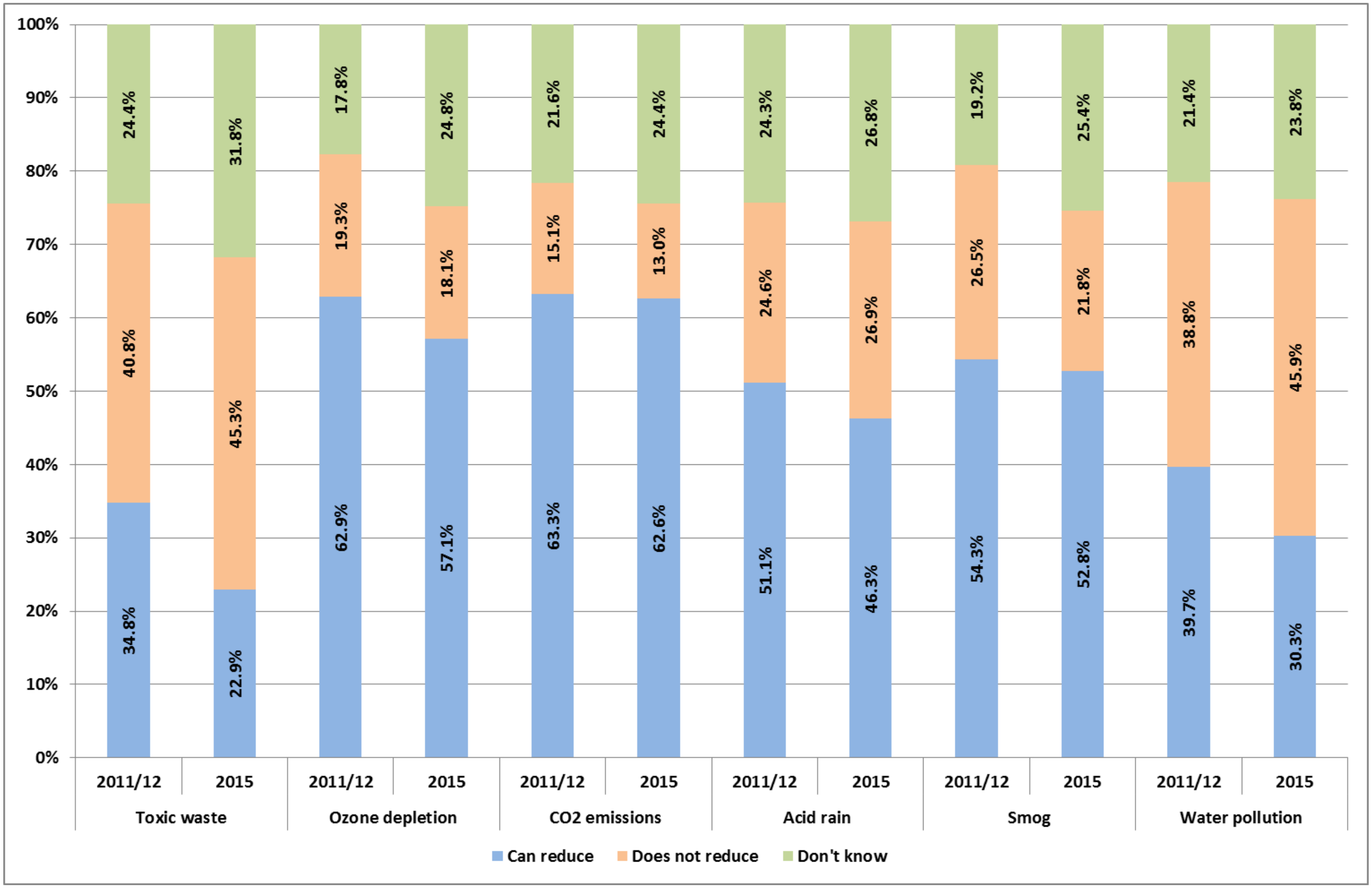

Fig. 2. Factual knowledge about CCS.

Only respondents who had heard about CCS. Data sources: IEK-STE Panel Survey 2011/12 (n=569), 2015 (n=492). Question: “Which of the following environmental concerns can CCS reduce?”

The results of our descriptive statistical analyses illustrate that self-reported awareness about CCS decreased in 2013 compared to 2011/12 (cf. Figure 1). In 2011/12, 43.1 % of the German public had never heard about CCS, in 2013 in contrast 51.2 % answered that they had never heard of CCS. The proportion of respondents who answered that they heard quite a bit about CCS decreased from 15.2 % to 9.4 %.

Since 2013 the self-reported awareness about CCS has mainly remained stable, with around 51 % of respondents who had never heard of CCS.

The proportion of respondents who answered that they heard a little bit about CCS amounted to 40% to 42% and the share of respondents who answered that they had heard quite a bit about CCS decreased from 9 % to 8 %.

In contrast, the self-reported awareness about shale gas and fracking increased continuously over time. In 2011/12, 75 % of the German public had never heard of shale gas, in 2015 in contrast 61.6 % had never heard of it. The proportion of respondents who answered that they had heard quite a bit about shale gas increased from 5.1 % to 9.5 %.

The self-reported awareness about fracking increased considerably more over time than the self-reported awareness about shale gas: in 2011/12, 80.9% of the German public had never heard of fracking, whereas in 2015 only 38.0 % had never heard of it. The share of respondents who answered that they had heard quite a bit about fracking increased from 4.2 % to 20.1 %. Figure 1 also shows that self-reported awareness about fracking particularly increased from 2014 to 2015.

The differences in self-reported awareness about CCS, shale gas and fracking reflect the different status of public debate and media coverage regarding these topics in the last few years. Whereas the development of CCS in Germany has slowed down and is suspended at present (cf. Fischer, 2014), the regulation of shale gas extraction in Germany and Europe has been intensively discussed and has been accompanied by several extensive media reports.[9]

3.2. Factual knowledge about CCS and shale gas extraction

Knowledge of an object or issue can be measured on a subjective level or on a factual level, cf. (European Commission, 2008). The factual knowledge about CCS among the German public was measured in our panel survey by asking the question "Which of the following environmental concerns can CCS reduce?" and then presenting the following environmental concerns: toxic waste, ozone depletion, CO_2 emissions, acid rain, smog and water pollution (cf. Figure 2). The question was posed only to respondents who had heard of CCS (cf. Section 3.1).

The results of this question indicate that the level of factual knowledge about CCS among the German public has increased over time with regard to some aspects, whereas it has remained stable with regard to others (cf. Figure 2). The share of respondents who knew that CCS does not reduce toxic waste increased by 4.5 percentage points and the share of respondents who knew that CCS does not reduce water pollution increased by 7 percentage points in 2015, compared to 2011/12. The share of respondents who correctly stated that CCS does not reduce acid rain increased from 24.6 % to 26.9 %. On the other hand, the proportion of respondents who knew that CCS can reduce CO_2 emissions was around 63 % in both years.

However, the results also show that misconceptions about CCS exist and persist over time. In 2011/12, 62.9 % and in 2015 57.1 % of the respondents incorrectly thought that CCS can reduce ozone depletion. Furthermore, in both years more than half of the respondents incorrectly thought that

[9] http://www.shale-gas-information-platform.org/areas/the-debate/shale-gas-in-germany-the-current-status.html.

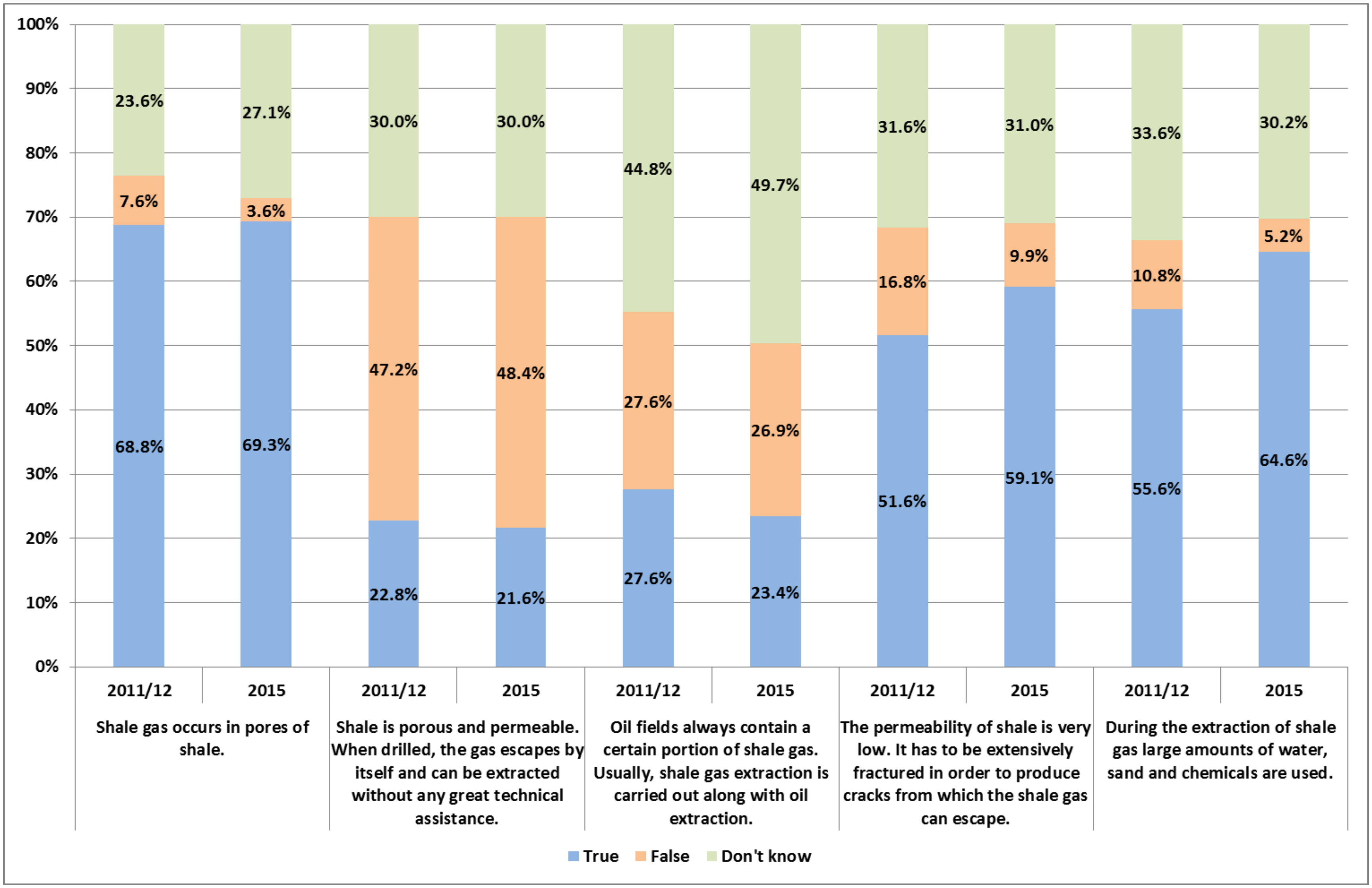

Fig. 3. Factual knowledge about shale gas extraction.

Only respondents who had heard about shale gas. Data sources: IEK-STE Panel Survey 2011/12 (n=250), 2015 (n=384). Question: “Please tell me to the best of your knowledge whether each statement is true or false.”

CCS can reduce smog.

In order to find out the factual knowledge of German citizens about shale gas extraction, the respondents in our surveys who had heard about shale gas were presented with the five statements shown in Figure 3 and then asked whether these statements were true or false. The results show that, similar to CCS, the level of knowledge about shale case extraction has increased over time, but only with regard to some aspects.

The share of respondents who knew that during the extraction of shale gas large amounts of water, sand and chemicals are used, increased by 9 percentage points in 2015, compared to 2011/12. The proportion of respondents who knew that the permeability of shale is very low so that it has to be fractured in order to produce cracks from which the shale gas can escape rose by 7.5 percentage points. On the other hand, the share of respondents who knew that shale gas occurs in pores of shale remained stable over time.

Furthermore, with regard to shale gas extraction misconceptions also exist which persist over time. For example, the proportion of respondents who incorrectly thought that shale is porous and permeable so that the shale gas can be extracted without any great technical assistance when the shale is drilled was 22.8 % in 2011/12 and 21.6 % in 2015.

Additionally, the proportions of respondents who did not know whether shale gas occurs in pores of shale or whether the extraction of shale gas is carried out along with oil extraction increased over time.

3.3. Risk perceptions of CO_2 pipelines, CO_2 onshore storage, CO_2 offshore storage and the extraction of shale gas

Previous studies on the acceptance of risks and technologies verified that the acceptance of technologies by the general public is greatly influenced by the intuitive perception of risks, as well as by the perception of benefits and trust (e.g. L′Orange Seigo et al., 2014, Siegrist, 2000, Siegrist et al., 2007). In our studies, we generally differentiate between the perception of personal risk, which means how hazardous respondents think an energy technology would be for them and their families and the perception of societal risk, which means how hazardous respondents think an energy technology would be for society in general (Schumann, 2015; Schumann et al., 2014). The risk perceptions are specified on a seven-level Likert scale, ranging from 1 (= very low) to 7 (= very high).

However, in our “CCS Chances Survey”, we collected data on the perceptions of the personal and societal risk of CO_2 transport via pipeline, CO_2 onshore storage and CO_2 offshore storage and not of CCS in general. This was due to the research focus of the project “CCS Chances”, which was the investigation of the perception of CO_2 offshore storage among the German public in comparison to the perception of CO_2 onshore storage and CO_2 transport via pipeline. Thus, in this paper we compared the risk perceptions of CO_2 pipelines, CO_2 onshore storage, CO_2 offshore storage and the extraction of shale gas (cf. Table 2).

With regard to the assessment of personal and societal risks of CO_2 transport via pipeline, CO_2 onshore storage, CO_2 offshore storage and the extraction of shale gas, a comparison of the means shows that the personal and societal risks of CO_2 onshore storage and shale gas are perceived as higher than the personal and societal risks of CO_2 pipelines and CO_2 offshore storage. However, in all cases the societal risks are deemed higher than the personal risks.

3.4. Benefit perceptions of CCS and the extraction of shale gas

With regard to the assessment of benefits, we also differentiate between the perception of the personal benefit and the perception of the societal benefit (Schumann, 2015). Benefit perceptions are also specified on a seven-level Likert scale, ranging from 1 (= very low) to 7 (= very high).

Due to the limited number of questions which we can pose in our surveys, it was not possible to include questions on the perceptions of personal and societal benefit of CO_2 pipelines, CO_2 onshore storage and CO_2 offshore storage, but only questions on the perceptions of personal and societal benefit of CCS (cf. Table 3).

Concerning the assessment of the benefits of CCS and shale gas, a comparison of means shows that the personal and societal benefits of shale gas are considered to be markedly lower than the personal and societal benefit of CCS. However, in both cases the societal benefit is perceived as higher than the personal benefit.

3.5. *General attitudes regarding CO_2 pipelines, CO_2 onshore storage, CO_2 offshore storage, CCS and the extraction of shale gas*

The general attitude regarding CO_2 transport via pipeline, CO_2 onshore storage, CO_2 offshore storage, CCS and the extraction of shale gas was measured in our surveys by asking the question "Overall, how do you assess the idea of CO_2 transport via pipeline/CO_2 onshore storage/CO_2 offshore storage/CCS/the extraction of shale gas?" The respondents specified their general attitude on a seven-level Likert scale, ranging from 1 (= very negative) to 7 (= very positive).

A comparison of means shows that the general attitude of the German public is considerably more negative towards shale gas than towards CO_2 pipelines, CO_2 onshore storage, CO_2 offshore storage and CCS (cf. Table 7). Furthermore, the general attitude is more negative towards CO_2 storage, especially CO_2 onshore storage, than towards CO_2 transport via pipeline and CCS in general.

3.6. *Determinants of general attitudes towards CO_2 pipelines, CO_2 onshore storage, CO_2 offshore storage and the extraction of shale gas*

In the previous sections, the self-reported awareness, factual knowledge, risk perceptions, benefit perceptions and general attitudes regarding CCS, CO_2 pipelines, CO_2 onshore storage, CO_2 offshore storage and the extraction of shale gas were compared by applying descriptive statistical analyses. In addition, the question of which factors determine general attitudes towards CO_2 transport, CO_2 storage and the extraction of shale gas is relevant. In order to answer this question, four linear regressions were performed (cf. Appendix).

Table 2. Risk perceptions of CO_2 pipelines, CO_2 onshore storage, CO_2 offshore storage and the extraction of shale gas.

	Personal risk		**Societal risk**	
	Mean[1]	SD[2]	Mean[1]	SD[2]
CO_2 transport via pipeline	3.7	1.8	4.1	1.6
CO_2 onshore storage	4.3	1.6	4.5	1.6
CO_2 offshore storage	3.9	1.8	4.2	1.7
Shale gas	4.2	1.7	4.7	1.6

[1] Scale from 1 (= very low) to 7 (= very high). [2] SD = standard deviation. Data sources: Survey "CCS Chances" 2013 (n= 1000); IEK-STE Panel Survey 2015 (n=1000). Question: "How hazardous do you think CO_2 transport via pipeline/CO_2 onshore storage/CO_2 offshore storage/the extraction of shale gas would be for you and your family/for society in general?"

Table 3. Benefit perceptions of CCS and the extraction of shale gas.

	Personal risk		**Societal risk**	
	Mean[1]	SD[2]	Mean[1]	SD[2]
CCS	3.4	1.6	3.9	1.7
Shale gas	2.8	1.4	3.4	1.5

[1] Scale from 1 (= very low) to 7 (= very high). [2] SD = standard deviation. Data sources: Survey "CCS Chances" 2013 (n= 1000); IEK-STE Panel Survey 2015 (n=1000). Question: "To what extent do you think CCS/the extraction of shale gas would benefit you and your family/society in general?"

Table 4. General attitudes regarding CO_2 pipelines, CO_2 onshore storage, CO_2 offshore storage, CCS and the extraction of shale gas.

	General attitude	
	Mean[1]	SD[2]
CO_2 transport via pipeline	3.9	1.6
CO_2 onshore storage	3.3	1.7
CO_2 offshore storage	3.6	1.8
CCS	3.8	1.7
Shale gas	2.9	1.6

[1] Scale from 1 (= very negative) to 7 (= very positive). [2] SD = standard deviation. Data sources: Survey "CCS Chances" 2013 (n= 1000); IEK-STE Panel Survey 2015 (n=1000). Question: "Overall, how do you assess the idea of CO_2 transport via pipeline/CO_2 onshore storage/CO_2 offshore storage/CCS/the extraction of shale gas?"

The results of our regression analyses[10] show that the most important direct determinants of general attitudes towards CO_2 pipelines, CO_2 onshore storage, CO_2 offshore storage and the extraction of shale gas are the perceptions of personal and societal risks.[11] The perception of societal risk has the highest estimated parameter in every regression model, followed by the perception of personal risk (cf. Appendix). Furthermore, the perceptions of societal and personal risk revealed negative correlations with the general attitude in every regression model, i.e. the higher the perceived personal or societal risk, the more negative is the general attitude towards CO_2 pipelines, CO_2 onshore storage, CO_2 offshore storage or the extraction of shale gas.

The perception of societal benefit is an important positive determinant of the general attitude in all regression models: the higher the assessed societal benefit, the more positive is the general attitude towards CO_2 transport via pipeline, CO_2 onshore storage, CO_2 offshore storage or the extraction of shale gas.

The perception of personal benefit is an important positive determinant of general attitudes towards CO_2 onshore storage, CO_2 offshore storage and shale gas extraction, i.e. the higher the assessed personal benefit, the more positive is the general attitude. For the general attitude regarding CO_2 pipelines, the perception of personal benefit is not a statistically significant influence factor.

The general attitudes towards CO_2 transport via pipeline, CO_2 onshore storage and CO_2 offshore storage are also influenced weakly positively by the perception of nature as tolerant[12], whereas the perception of nature as benign is a positive determinant of general attitudes towards CO_2 onshore storage and CO_2 offshore storage. The perception of nature as capricious determines the general attitude towards shale gas extraction weakly positively. In contrast, the general attitude of CO_2 offshore storage is influenced weakly negatively by the perception of nature as ephemeral.

The perception that both the environment and the economy are important, but the economy should come first, determines general attitudes towards CO_2 transport via pipeline, CO_2 onshore storage and CO_2 offshore storage weakly positively, whereas the influence of this factor is slightly stronger with respect to the general attitude towards CO_2 pipelines. A weakly positive determinant of the general attitude towards shale gas extraction is the perception that decisions on policy and economy regarding technology are often made over citizens' heads.

[10] The fit indices in the appendix show a good fit for all regression models performed.

[11] This confirms the results of other empirical studies on public perception of CCS (L'Orange Seigo et al., 2014).

[12] For the explanation of attitudes towards the vulnerability of nature see (Schumann et al., 2014).

4. Conclusions

Using the examples of CCS and the extraction of shale gas, this study shows that technology monitoring contributes to the assessment of the public perception of energy system transformation by three different functions: (1) a descriptive, (2) a comparative, and (3) an explanatory function.

The descriptive function of technology monitoring is to provide information about the awareness, the knowledge and the attitudes of the public regarding technologies, instruments and impacts of energy transition. This includes information about the status quo within the survey period as well as about the development over time.

The comparative function of technology monitoring enables similarities and differences to be identified between the perceptions of different technologies, instruments and impacts of energy transition. This makes possible to ascertain which characteristics are specific for the respective technology or instrument and which are not, and to derive generalizable conclusions. However, such a systematic comparison requires that the perceptions of different technologies, instruments and impacts are measured with the same indicators, such as self-reported awareness, factual knowledge and attitudes.

Furthermore, technology monitoring has an explanatory function, which was demonstrated in this study by identifying important determinants of general attitudes regarding energy technologies.

All three functions of technology monitoring provide information which can be used for assessing public perception of different energy transition paths. This can be done, for example, by integrating indicators of public perception either ex ante as input parameters or ex post as output parameters in energy scenario construction processes (Schubert et al., 2015). Integrating public perception indicators as input parameters would be helpful for generating holistic scenarios, whereas integrating public perception indicators as output parameters would be useful for generating normative scenarios [ibid.]. Both ways of integrating public perception indicators in energy scenarios can be valuable in order to assess the societal feasibility of future energy systems and delivering information which can facilitate the management of energy transition.

Acknowledgements

Some of the data used in this study were collected in the project “Chances for and Limitations of Acceptance for CCS in Germany (CCS Chances)”, for which we gratefully acknowledge funding from the Federal Ministry of Education and Research.

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Appendix

Table 5: Variables in the regression models

Model	Dependent variable	Independent variables
Model 1	General attitude towards CO_2 transport via pipeline	• Gender • Age • Professional qualifications • Factual knowledge about pipelines • Perception of the personal risk of CO_2 transport via pipeline • Perception of the societal risk of CO_2 transport via pipeline • Perception of the personal benefit of CCS • Perception of the societal benefit of CCS • Attitudes towards the vulnerability of nature • Attitudes towards the relation of economy and environment
Model 2	General attitude towards CO_2 offshore storage	• Gender • Age • Professional qualifications • Factual knowledge about CO_2 storage • Perception of the personal risk of CO_2 offshore storage • Perception of the societal risk of CO_2 offshore storage • Perception of the personal benefit of CCS • Perception of the societal benefit of CCS • Attitudes towards the vulnerability of nature • Attitudes towards the relation of economy and environment
Model 3	General attitude towards CO_2 onshore storage	• Gender • Age • Professional qualifications • Factual knowledge about CO_2 storage • Perception of the personal risk of CO_2 onshore storage • Perception of the societal risk of CO_2 onshore storage • Perception of the personal benefit of CCS • Perception of the societal benefit of CCS • Attitudes towards the vulnerability of nature • Attitudes towards the relation of economy and environment
Model 4	General attitude towards the extraction of shale gas	• Gender • Age • Professional qualifications • Factual knowledge about shale gas extraction • Perception of the personal risk of shale gas extraction • Perception of the societal risk of shale gas extraction • Perception of the personal benefit of shale gas extraction • Perception of the societal benefit of shale gas extraction • Attitudes towards the vulnerability of nature • Perceptions of technology

Results of the linear regression models

Model 1: General attitude towards CO_2 transport via pipeline

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.652	.426	.416	1.207

ANOVA

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	989.404	16	61.838	42.438	.000
	Residual	1334.727	916	1.457		
	Total	2324.131	932			

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients		
		B	Std. Error	Beta	t	Sig.
1	(Constant)	4.712	.330		14.277	.000**
	Gender	.012	.083	.004	.145	.885
	Age	-.006	.002	-.064	-2.428	.015*
	Professional qualifications	.024	.045	.013	.532	.595
	Factual knowledge about pipelines	.089	.031	.076	2.899	.004*
	Perception of the personal risk of CO_2 transport via pipeline	-.194	.042	-.214	-4.631	.000**
	Perception of the societal risk of CO_2 transport via pipeline	-.302	.044	-.309	-6.835	.000**
	Perception of the personal benefit of CCS	.076	.040	.079	1.907	.057
	Perception of the societal benefit of CCS	.157	.039	.168	4.033	.000**
	Perception of nature as benign	.013	.030	.013	.433	.665
	Perception of nature as tolerant	.080	.022	.094	3.544	.000**
	Perception of nature as ephemeral	-.049	.029	-.050	-1.731	.084
	Perception of nature as capricious	-.025	.024	-.029	-1.064	.288
	The highest priority should be given to protecting the environment. even if it hurts the economy	-.012	.030	-.012	-.402	.688
	Both the environment and the economy are important. but the environment should come first	.014	.033	.014	.429	.668
	Both the environment and the economy are important. but the economy should come first	.090	.027	.103	3.402	.001**
	The highest priority should be given to economic considerations even if it hurts the environment	-.013	.029	-.015	-.464	.643

a. Dependent variable: General attitude towards CO_2 transport via pipeline. Method=enter.
** $p<=0.001$, * $p<=0.05$

Model 2: General attitude towards CO_2 offshore storage

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
2	.716	.513	.504	1.256

ANOVA

Model		Sum of Squares	df	Mean Square	F	Sig.
2	Regression	1519.657	16	94.979	60.191	.000
	Residual	1445.406	916	1.578		
	Total	2965.063	932			

Coefficients[a]

Model		Unstandardized Coefficients B	Unstandardized Coefficients Std. Error	Standardized Coefficients Beta	t	Sig.
2	(Constant)	3.099	.346		8.967	.000**
	Gender	.001	.088	.000	.012	.991
	Age	.000	.003	.002	.077	.938
	Professional qualifications	.091	.047	.045	1.925	.055
	Factual knowledge about CO_2 storage	.060	.028	.051	2.152	.032*
	Perception of the personal risk of CO_2 offshore storage	-.185	.036	-.189	-5.188	.000**
	Perception of the societal risk of CO_2 offshore storage	-.337	.039	-.328	-8.711	.000**
	Perception of the personal benefit of CCS	.093	.041	.086	2.297	.022*
	Perception of the societal benefit of CCS	.184	.041	.174	4.541	.000**
	Perception of nature as benign	.139	.032	.122	4.393	.000**
	Perception of nature as tolerant	.073	.024	.077	3.112	.002*
	Perception of nature as ephemeral	-.059	.030	-.053	-1.945	.052*
	Perception of nature as capricious	.022	.024	.022	.893	.372
	The highest priority should be given to protecting the environment. even if it hurts the economy	.054	.031	.050	1.739	.082
	Both the environment and the economy are important. but the environment should come first	.064	.035	.056	1.838	.066
	Both the environment and the economy are important. but the economy should come first	.074	.028	.075	2.695	.007*
	The highest priority should be given to economic considerations even if it hurts the environment	-.001	.030	-.001	-.025	.980

a. Dependent variable: General attitude towards CO_2 offshore storage. Method=enter.
** $p<=0.001$. * $p<=0.05$

Model 3: General attitude towards CO_2 onshore storage

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
3	.642	.412	.402	1.275

ANOVA

Model		Sum of Squares	df	Mean Square	F	Sig.
3	Regression	1044.054	16	65.253	40.166	.000
	Residual	1488.135	916	1.625		
	Total	2532.189	932			

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
3	(Constant)	4.058	.356		11.409	.000**
	Gender	.054	.088	.016	.619	.536
	Age	-.006	.003	-.063	-2.387	.017*
	Professional qualifications	-.034	.048	-.018	-.718	.473
	Factual knowledge about CO_2 storage	.027	.028	.025	.960	.337
	Perception of the personal risk of CO_2 onshore storage	-.162	.041	-.162	-3.930	.000**
	Perception of the societal risk of CO_2 onshore storage	-.356	.042	-.355	-8.521	.000**
	Perception of the personal benefit of CCS	.114	.041	.113	2.788	.005*
	Perception of the societal benefit of CCS	.137	.041	.140	3.369	.001**
	Perception of nature as benign	.080	.032	.076	2.478	.013*
	Perception of nature as tolerant	.060	.024	.068	2.507	.012*
	Perception of nature as ephemeral	.009	.030	.009	.295	.768
	Perception of nature as capricious	-.025	.025	-.027	-1.005	.315
	The highest priority should be given to protecting the environment. even if it hurts the economy	.021	.031	.021	.673	.501
	Both the environment and the economy are important. but the environment should come first	.032	.035	.031	.915	.360
	Both the environment and the economy are important. but the economy should come first	.060	.028	.065	2.129	.034*
	The highest priority should be given to economic considerations even if it hurts the environment	-.006	.031	-.006	-.189	.850

a. Dependent variable: General attitude towards CO_2 onshore storage. Method=enter.
** $p<=0.001$. * $p<=0.05$

Model 4: General attitude towards shale gas extraction

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
4	.789	.622	.615	1.007

ANOVA

Model		Sum of Squares	df	Mean Square	F	Sig.
4	Regression	1638.800	17	96.400	94.998	.000
	Residual	996.496	982	1.015		
	Total	2635.296	999			

Coefficients[a]

Model		Unstandardized Coefficients B	Unstandardized Coefficients Std. Error	Standardized Coefficients Beta	t	Sig.
4	(Constant)	3.050	.315		9.677	.000**
	Gender	.111	.068	.034	1.625	.104
	Age	.002	.002	.023	1.069	.285
	Professional qualifications	-.003	.035	-.002	-.096	.923
	Factual knowledge about shale gas extraction	-.021	.021	-.022	-1.014	.311
	Perception of the personal risk of shale gas extraction	-.119	.029	-.125	-4.107	.000**
	Perception of the societal risk of shale gas extraction	-.360	.032	-.350	-11.145	.000**
	Perception of the personal benefit of shale gas extraction	.201	.034	.179	5.945	.000**
	Perception of the societal benefit of shale gas extraction	.350	.034	.318	10.314	.000**
	Perception of nature as benign	.023	.021	.024	1.070	.285
	Perception of nature as tolerant	.007	.020	.007	.331	.741
	Perception of nature as ephemeral	-.017	.023	-.017	-.754	.451
	Perception of nature as capricious	.037	.018	.042	2.037	.042*
	Technology guarantees the competitiveness of our country and is important so that Germany can keep up with globalization	-.004	.025	-.003	-.158	.875
	Technology makes our life too fast-moving and untransparent and means that we can no longer concentrate on the important things in life	-.015	.022	-.017	-.710	.478
	Technology is one crucial cause of negative impacts on the environment. climate and health	-.018	.023	-.018	-.764	.445
	Decisions of policy and economy regarding technology are often made over citizens' heads	.058	.028	.050	2.112	.035*
	New ways should be found in order to involve citizens more closely in decisions regarding the use of technology	-.041	.026	-.036	-1.556	.120

a. Dependent variable: General attitude towards shale gas extraction. Method=enter.
** p<=0.001. * p<=0.05

Общественное восприятие трансформации энергетической системы в Германии

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Краткое изложение: Преобразование энергетической системы, также называемое энергетическим переходом, означает фундаментальные структурные изменения в энергетических системах. Основными задачами энергетического перехода в Германии, известными как «Energiewende», являются декарбонизация энергоснабжения путем перехода на возобновляемые источники энергии и снижения энергопотребления с использованием энергии все более и более эффективно. Это требует, например, изменений в структуре потребления энергоресурсов, применения новых энергетических технологий или изменения динамики спроса граждан. Однако такие стратегии трансформации, даже если они технически и экономически осуществимы, могут стать политически неосуществимыми, если они не будут приняты общественностью. Поэтому надежная оценка общественного восприятия необходима для успешного управления преобразованием энергетической системы.

Цель статьи - объяснить и проиллюстрировать, как инструмент, называемый технологическим мониторингом, используется для оценки общественного восприятия трансформации энергетической системы Германии. После описания исследовательских вопросов, изученных технологическим мониторингом, а также элементов и методов инструмента, два примера используются для иллюстрации того, как технологический мониторинг может способствовать оценке общественного восприятия трансформации энергетической системы: улавливание и хранение углекислого газа (УХУ) и добыча сланцевого газа. С этой целью общественное восприятие УХУ и добычи сланцевого газа в Германии сначала сравниваются по показателям самостоятельно представленной осведомленности, фактических знаний, восприятия риска, восприятия преимуществ и общих установок путем применения описательного статистического анализа.

Результаты описательного статистического анализа показывают различия во времени в самостоятельной осведомленности об УХУ и сланцевом газе. Уровень знаний об обеих технологиях с течением времени увеличивался с точки зрения некоторых аспектов, в то время как он оставался стабильным в отношении других. В то же время заблуждения об УХУ и добыче сланцевого газа среди общественности существуют и сохраняются с течением времени.

Описательный статистический анализ также показал, что общественные риски хранения углекислого газа, транспортировки углекислого газа и сланцевого газа считаются выше личных рисков и что общественные выгоды воспринимаются как более высокие, чем личные выгоды. Общее отношение немецкой общественности значительно более негативно относится к сланцевому газу, чем к передаче углекислого газа по трубопроводу, хранению углекислого газа и УХУ. Кроме того, наземное хранение углекислого газа оценивается более негативно, чем морское хранение углекислого газа, передача углекислого газа по трубопроводу или УХУ.

Были проведены четыре линейные регрессии с целью определения детерминантов отношений к передаче углекислого газа по трубопроводу, наземному хранению углекислого газа, морскому хранению углекислого газа и добыче сланцевого газа. Результаты показывают, что наиболее важными прямыми детерминантами общего отношения к передаче углекислого газа по трубопроводу, наземному хранению углекислого газа, морскому хранению углекислого газа и добыче сланцевого газа являются восприятие личных и социальных рисков.

Таким образом, с использованием примеров УХУ и добычи сланцевого газа настоящее исследование показывает, что технологический мониторинг способствует оценке общественного восприятия энергетической системы путем предоставления информации, которая может быть полезной для оценки социальной осуществимости энергетических систем в будущем, и информации, которая может способствовать управлению процессом энергетического перехода.

Ключевые слова: общественное восприятие, трансформация энергетической системы, Германия, технологический мониторинг, улавливание и хранение углекислого газа, добыча сланцевого газа.

A methodology to insert end-users behaviour in energy efficiency scenario modelling[13]

by

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Abstract

Deviations from the fulfillment of Energy Efficiency (EE) targets are attributed mainly to barriers created by the behavioral patterns of end-users. The methodology, based on the Analytical Hierarchy Process (AHP), concerns the calculation and interlinkage of the total impact factors of behavioral barriers demonstrated by end-users with the input drivers in the EE modeling. Two sets of behavioral barriers for buildings and transport are provided. Comments, advantages and disadvantages are discussed in the conclusions.

Keywords

Energy efficiency, behavioral barriers, impact factor, energy modelling.

1. Introduction

Energy Efficiency (EE) consists one of the main pillars of efforts to mitigate climate change (IEA, 2014; Energy Efficiency Financial Institutions Group, 2015). There is plethora of policy instruments that support the penetration of EE technologies and practices. Different types of barriers, particularly those linked with end-users behaviour, affect negatively the achievement of such targets (McCollum L. David et al., 2016; European Commission, 2015a, 2015b; European Environmental Agency, 2013). As a consequence, EE policies and measures do not deliver the expected benefits (such as energy savings, reductions in Greenhouse Gases (GHG), employment, poverty alleviation etc) (UNEP, 2014; IEA, 2014).

[13] The methodology was developed and implemented in the frame of the Horizon 2020 Research and Innovation project HERON (Grant Agreement No. 649690).

According to the Energy Efficiency Communication of July 2014, the EU is expected to miss the 20% energy savings target of year 2020 by 1% - 2% (European Commission, 2015a; 2015b; 2014; European Commission – Directorate - General for Energy, 2012). In 2014, three Member States (Estonia, Malta and Sweden) had not achieved sufficient savings in primary energy consumption (EEA, 2016a). Due to this fact, Malta's 2020 EE target, expressed in final energy consumption, was increased in 2015 from 0.493Mtoe to 0.547Mtoe, becoming less ambitious since this amount is increased instead of being reduced even more (European Commission, 2015a). The Dutch Government lowered its initial reduction target from 30% to 20% (Vringer K. et al., 2016). Three other EU Member States (Germany, Lithuania and Slovakia) had not succeeded in their efforts of reducing sufficiently their final energy consumption so as to remain below their linear trajectory (EEA, 2016b).

Currently, efforts are focused in overcoming existing barriers and increasing the sophistication of energy and economic modelling (European Commission (EC), 2015b; 2014). Key insights in the outcomes of such efforts can guide the effective design and implementation of end-user-focused strategies and public policy interventions to improve the level of EE interventions (by adopting technologies or practices) (Frederiks R. et al., 2015; UNEP, 2014).

Forward-looking models are used for medium-to-long-term scenario analyses, aiming to support relevant policy options; some of these models are designed to consider both technological, economical and socio-behavioral elements in developing the scenarios (McCollum L. David et al., 2016; Knoblocha F., Mercure J.-F., 2016). Bridging the gap between these elements has historically been presented as a challenge (McCollum L. David et al., 2016). Demands of improving the design of models so as to become more 'realistic' by incorporating features observed in the real world are increasing (McCollum L. David et al., 2016). One group of such features of the 'real world' relates to human behaviour. Barriers, related to end-users' behaviour, need to be incorporated in forward looking EE modelling after being identified and analysed (McCollum L. David et al., 2016; EC, 2015a, 2015c; EEA, 2013).

The aforementioned demands are based on the following arguments (McCollum L. David et al., 2016):

i) Models lacking behavioural realism are restricted in evaluating energy efficiency policies and other influences on end-user demand;
ii) Improving the behavioural realism of models consequently affects policy-relevant model analysis of EE as part of the climate change mitigation efforts.

However, current modelling of behavioural features in energy-economy and integrated assessment models is relatively limited (McCollum L. David et al., 2016). Models and particularly Integrated Assessment Models (IAMs) represent the behaviour of consumers or energy end-users through economic relationships: energy demand as a function of price, technology investments to minimize levelized costs, etc (McCollum L. David et al., 2016).

End-user behaviour is complex and rarely follows traditional economic theories of decision-making (McCollum L. David et al., 2016; Frederiks R. et al., 2015; Knoblocha F., Mercure J.-F., 2016). End-users patterns of energy consumption are influenced by social-cultural-educational (status quo, social interactions etc), economic (risks of investment, financial incentives) and institutional factors (split incentives, hassle factor etc) that are characterized as barriers (Vringer K. et al., 2016; Frederiks R. et al., 2015; UNEP, 2014).

Consequently, a methodology inserting end-users' behavior into forward looking EE modeling adds value in efforts to have more reliable EE modeling.

2. Methodology

2.1. Concept

Developed scenarios for EE include as key drivers (or assumptions) the penetration of EE technologies (Building shell improvement, efficient heating and cooling, heat pumps, more efficient vehicles, etc.) and their supportive policy package (energy labelling, building standards, fuel taxes etc) (IEA, 2013; European Communities, 2006). The assumed shares of such technologies combined with the appropriate policy instruments form the synthesis of various scenarios developed with the use of energy models such as LEAP, MARKAL, TIMES, POLES etc (Bhattacharyya C. S. and Timilsina R. G., 2010).

The EE target set for a country depends on the aforementioned combination and the consumers' habits and behavior (IEA, 2013). Each national economic sector has its own EE targets or assigned contribution to the national EE target. Simultaneously, each sector has its own set of barriers towards EE issues (Hochman G. and Timilsina G. R., 2017; Trianni A. et al., 2016; Johnson H. and Anderson K., 2016; HERON, 2015a; HERON, 2015b). Depending on the rationality of these scenarios, assumptions are adopted for overcoming identified existing barriers. Each identified barrier, due to end-users' behavior towards EE issues, has a different impact in limiting the efforts of achieving any type of energy efficiency target. Quantification of the qualitative information of identified barriers allows the numerical expression of the respective impact factors on the inputs for the forward-looking EE modelling.

The proposed methodology transforms qualitative research outcomes about barriers linked to end-users' behavior, into quantitative ones. With the use of the Analytical Hierarchy Process (AHP), comparative analysis is conducted among these barriers due to end users' behavior towards technologies, measures and policy instruments for achieving EE targets. This process reveals and quantifies the negative impact of each barrier on the set of the assumed targets, in EE modeling. Mathematical expressions using the calculated impact factor of barriers provide numerical inputs to energy modelling reflecting the deviation from the set EE target due to end-users' behavior. Once the procedure is completed, the policy maker can modify accordingly the available inputs so as to reduce the calculated deviation.

2.2. *Rationale for the AHP choice*

The selection of the AHP allows pair-wise comparisons among the objects that need to be assessed (either criteria/sub-criteria, alternatives, options or barriers). Furthermore, it has the following advantages:

- *AHP is justified mathematically* (specifically, it is mathematical theory of value, reason and judgment, based on ratio scales) (Eakin H., Bojorquez-Tapia L.A., 2008; Kablan M.M., 2004).
- *AHP presents better the problem.* Its main advantage is the decomposition of the problem into elements (Ishizaka A., Labib A., 2011; Berrittella et al., 2008). Its hierarchical structure of criteria allows users to focus better on specific criteria and sub-criteria when determining the respective weight coefficients through pairwise comparisons (Ishizaka A., Labib A., 2011).
- *AHP allows pairwise comparisons*. Psychologists argue that it is easier and more accurate to express one's opinion only on two alternatives[14] than simultaneously on all (Ishizaka A., Lablb A., 2011). Additionally, the usage of pairwise comparisons does not require the explicit definition of a measurement scale for each attribute (Bozdura F.T. et al., 2007).
- *AHP offers guidelines in defining the weight coefficients and has a consistency test*. "*The AHP approach employs a consistency test that can screen out inconsistent judgments, which*

[14] Since two alternatives form the pairwise comparisons of AHP

makes the results reliable." (Bongchul K. et al., 2017; Kablan M.M, 2004).

- *AHP is suitable for incorporating the preferences of relevant decision makers/stakeholders regarding the importance of the criteria/sub-criteria* (Bongchul K. et al., 2017; Fikret K.T., et al., 2016; Ananda J., Herath G., 2009). Due to this advantage, it has been widely used in energy management, business, maintenance engineering, and medical & health care, strategic planning etc (Da A. et al., 2017; Madeira G. J. et al., 2016). Reservations, though, are expressed that the method may be impractical for a survey with a large sample size of as 'cold-called[15]' respondents, because they may have a great tendency to provide arbitrary answers, resulting in a very high degree of inconsistency (Wong K.W.J., Li H., 2008). But there are scholars that support that it can handle uncertain, imprecise and subjective data (Srdjevic B., Medeiros Y.D.P., 2008; Petkov D. et al., 2007).

- *AHP allows qualitative and quantitative approaches for solving a problem* (Madeira G. J. et al., 2016; Kilincci O., Onal S.A., 2011; Wong J.K.W., Li H., 2008; Duran O., Aguilo J., 2008). The user can deal in this way the inherent subjectivity of the selection process. Pair-wise comparisons are quantified by using a scale (Stefanovic G. et al., 2016).

- *AHP has high popularity.* Comparative analysis of Multi Criteria Decision Analysis (MCDA) approaches has indicated AHP to be the most popular compared to other methods due to its simplicity, easiness to use and great flexibility (Nasirov S. et al., 2016; Kilincci O., Onal S.A., 2011; Ho W. et al., 2010; Srdjevic B., Medeiros Y.D.P., 2008; Duran O., Aguilo J., 2008; Babic Z., Plazibat N., 1998).

  The method reproduces what seems to be a natural method of human mind in perceptions and judgements (Madeira G. J. et al., 2016). It does not require explicit quantification of criteria (Zietsman D., Vanderschuren M., 2014). The users may directly input judgment data without getting into the mathematical background (Duran O., Aguilo J., 2008).

- *AHP has been used only for the determination of the importance of criteria/factors* (alone or in combination with other multi-criteria decision analysis methods) (Kuruoglu E. et al., 2015; Kumar S. et al., 2015; Andrejiova M. et al., 2013).

2.3. Outline and steps

The methodology, based on the AHP, develops a road map consisted of six steps. It starts with "Mapping, categorization and merging behavioral barriers" (step 1), proceeds with the "Development of the AHP tree and matrices" (step 2), the "Calculation of weight coefficients" (step 3), the "Definition and calculation of the Impact Factors of barriers" (step 4), the "Linkage of Impact factors of barriers with technologies and policies (step 5) and concludes with the "Incorporation of the Total Impact Factors in the forward-looking EE modelling" (step 6).

Step 1: Mapping, categorization and merging of behavioral barriers

The mapping of barriers linked with end-users' behavior towards EE issues is defined by the requirements of the EE scenario modelling (sector and EE technologies). Barriers are sought through: i) Bibliographic research (National Action Plans, Strategies, National Communications, reports from target groups (associations of household owners, chambers, projects etc), published papers); ii) interviews or questionnaire survey (Hochman G. and

[15] A telephone call or visit made to someone who is not known or not expecting contact.

Timilsina R. G., 2017; Chiaroni D. et al., 2016; HERON, 2015a; 2015b).

The identified barriers, with the same basic characteristics, are categorized into main groups and sub-groups. Each main group is divided into subgroups if there is a large number of identified barriers. Based on literature research three main groups are foreseen for barriers linked with end-users' behavior: "Social-Cultural-Educational" (S-C-E), "Economic" (EC) and "Institutional" (IN) (Nasirov S. et al., 2016; UNEP, 2014; IEA, 2014, 2013; EEA, 2013; Energy Communities, 2006). The first group is divided into three sub-groups "Social (S)", "Cultural (C)" and "Educational (E)".

Barriers with the same content; behavior or same manner in being handled, are merged into one barrier with a common title. This action is necessary so that the final set of barriers is complete, non-redundant, minimalistic, non-overlapping, mutually independent, decomposable (Zietsman D., Vanderschuren M., 2014; Makropoulos C.K. and Butler D., 2006).

Step 1 based on the aforementioned sources and the findings of the HERON project led to two sets of behavioral barriers with universal use, responding to the needs of forward looking EE modelling for the sectors of buildings and transport (HERON, 2015a; 2015b; 2016). These sets are presented in the next step.

Step 2: Development of the AHP tree and matrices

The mapped and classified barriers into groups and sub-groups of step 1 form the AHP tree. Apart from the structure of groups and sub-groups, the goal (zero level of AHP tree) needs to be determined also. Goal reflects the aim of the tree which is the "limiting efforts for achieving the EE target" due to the impact of each barrier as part of this tree (Figure 1). This EE target can be based on primary or final energy consumption, primary or final energy savings, or energy intensity[16].

The next level is the first level of the AHP tree and is structured with the three main groups of barriers: i) S-C-E); ii) EC and iii) IN. The second level consists of the three sub-groups S, C and E. The other two groups do not have sub-groups (Figure 1). Under each group and sub-group, the identified and merged barriers are classified forming the third level. The two sets of barriers of step 1 with the goal are presented in Tables 1 and 2. The comparison of these two sets shows that: i) The number of classified barriers is different for one sub-group (E) and two groups (EC, IN); ii) there are common barriers between the two sets.

This structure – common for both sectors - is used to form the AHP matrices for the comparative analysis of the next steps. Columns and rows of these matrices refer to the compared *groups* or *sub-groups of barriers* or *barriers themselves* (depending on the level forming the matrix). The AHP matrices are filled in their diagonal with number "1" due to the pairwise comparison of one group or sub-group or barrier with itself. The preferable maximum number for each AHP matrix is 8x8.

Step 3: Calculation of weight coefficients

Step 3.1: First level of pair-wise comparisons

The three *groups of barriers* (S-C-E; EC; IN) are compared using the AHP matrix and scale (Tables 3 and 4). Each cell of the AHP matrix is filled after:

i) comparing the group of each row with the respective group of the column;

ii) assigning the appropriate - according to judgement - intensity from Table 4;

iii) the assignment of the intensity (judgement) is based on the following conditions:

[16] https://ec.europa.eu/energy/en/topics/energy-efficiency/energy-efficiency-directive

a. the first group is more important compared to the second one if the number of the identified barriers under the first group of barriers is higher compared to those under the second one;

b. the first group is more important compared to the second one depending on the level of difficulty with which it can be confronted (the more difficult, the more important);

c. the first group is more important compared to the second one if it is divided in more different sub-groups; and

d. the first group is more important compared to the second one if the available preferences of experts on EE issues clearly quote this importance.

iv) Depending on how overall important is the first group, compared to the second; the intensity is assigned by the user. The selected intensity is quoted in the respective cell. If during any comparison, the second group is more important than the first one, then the quoted intensity is 1/intensity.

Table 5 shows a filled AHP matrix where A_{ij} is the content of the cell (i,j); i refers to the row and j to the column. The element of the AHP matrix, A_{12}, expresses how more important is the first group (S-C-E), in limiting the efforts of achieving the EE target compared to the second group of barriers (EC).

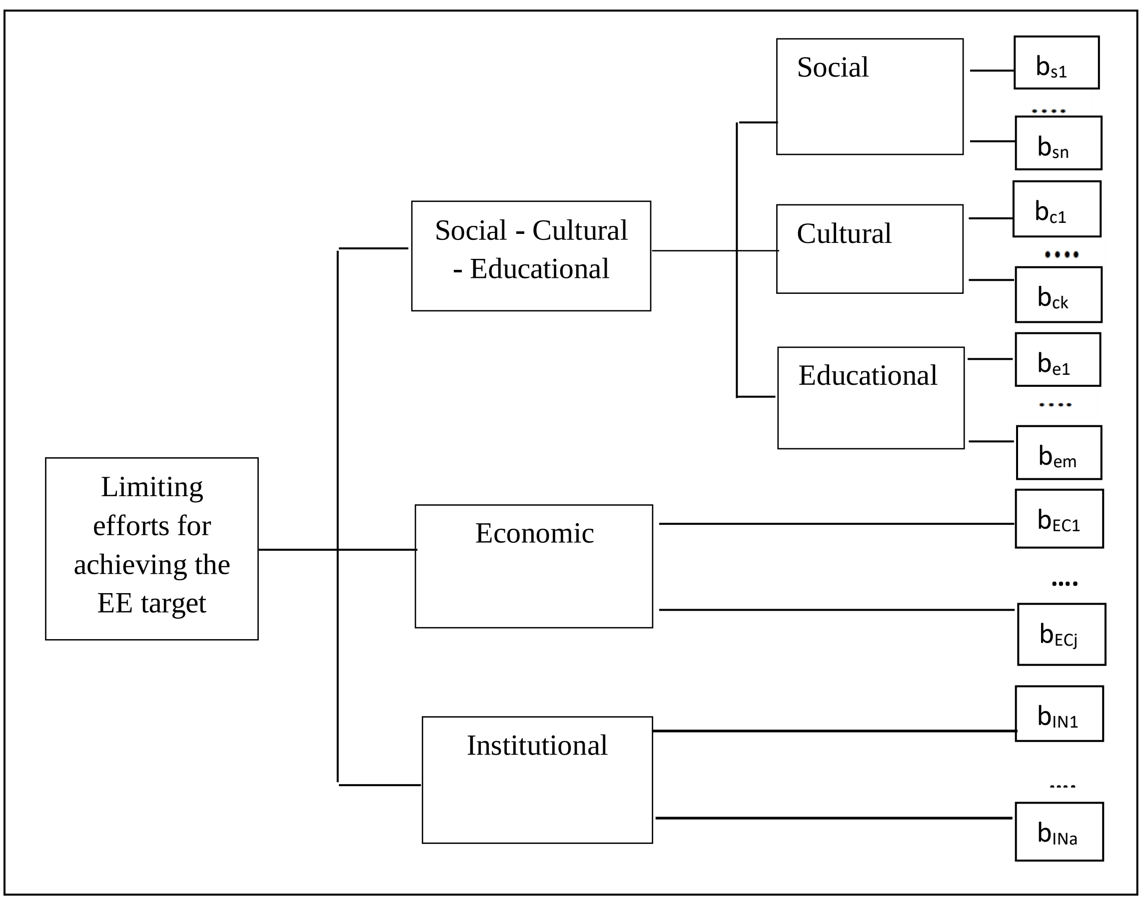

Fig 1: The AHP tree of the barriers.

Table 1. Set of behavioural barriers for the building sector.

Goal	Group	Sub-group	Barriers (b)
Limiting efforts for achieving the EE target	S-C-E	S	b_{s1}: Social group interactions and status considerations
			b_{s2}: Socio-economic status of building users
			b_{s3}: Strong dependency on the neighbors in multi-family housing
			b_4: Inertia
			b_{s5}: Commitment and motivation of public social support
			b_{s6}: Rebound effect
		C	b_{c1}: Lack of interest/low priority/Undervaluing energy efficiency
			b_{c2}: Customs, habits and relevant behavioural aspects
			b_{c3}: Bounded rationality/Visibility of energy efficiency
			b_{c4}: Missing credibility/mistrust of technologies and contractors
		E	b_{E1}: Lack of trained and skilled professionals/ trusted information, knowledge and experience
			b_{E2}: Lack of awareness/knowledge on savings potential/information gap on technologies
	EC		b_{EC1}: Lack of any type of financial support (lack of financial incentive (Public and Private sector)/ Lack of funds or access to finance)
			b_{EC2}: High capital costs/Financial risk/ Uncertainty on investment/ High cost of innovative technologies for end-users
			b_{EC3}: Payback expectations/investment horizons
			b_{EC4}: Relatively cheap energy and fuel prices/ misleading Tariff system not reflecting correct prices for energy use/EE
			b_{EC5}: Unexpected costs (Hidden costs/ Costs vary regionally (Fragmented ability))
			b_{EC6}: Financial crisis/Economic stagnation
			b_{EC7}: Embryonic markets
	IN		b_{IN1}: Split Incentive
			b_{IN2}: Legislation issues (Lack of relevant legislation/Lack of regulatory provision /Change of legislation for local/regional administrative division/ Complex/inadequate regulatory procedures)
			b_{IN3}: Building stock characteristics/aging stock/ Historical preservation
			b_{IN4}: Poor compliance with efficiency standards or construction standards/ Technical problems/ Performance gap/mismatch
			b_{IN5}: Lack of data/information-diversion of management
			b_{IN6}: Barrier to behavior change due to problematic Implementation Network (IN)/governance framework (Inadequate IN/governance framework /Inadequate implementation of policy measures / poor Policy coordination across different levels/cooperation of municipalities)
			b_{IN7}: Disruption/Hassie factor
			b_{IN8}: Security of fuel supply

Table 2. Set of behavioural barriers for the transport sector.

Goal	Group	Sub-group	Barrier
Limiting efforts for achieving the EE target	S-C-E	S	b_{s1}: Low satisfaction with public transport/lack of trust
			b_{s2}: Concerns of vehicle reliability/Hesitation to trust new technologies
			b_{s3}: Heterogeneity of consumers
			b_{s4}: Suburbanisation trends/Low density
			b_{s5}: Mobility problems (Vulnerability of pedestrians / Lack of adequate space for walking/ Cruising traffic/ Parking problems)
			b_{s6}: Inertia
		C	b_{c1}: Car as a symbol status and group influence
			b_{c2}: Habit and social norm of driving, car ownership and use
			b_{c3}: Cycling is marginalized
			b_{c4}: Attitude (Attitude-action gap /Bounded rationality/Buyer attitude)
		E	b_{E1}: Lack of knowledge/information (on green transport/ULEVs/EVs - fuel economy)
			b_{E2}: Low/Limited awareness (of impact of EE in transport /towards eco-driving/benefits-environmental impacts)
			b_{E3}: Confusion about car and fuel costs (conventional vs ULEVs/Evs) – *Negative perception*
			b_{E4}: Lack of certified instructors/examiners/technicians/professionals for eco-driving /integrated transport/mobility/ ULEVs/Evs
	EC		b_{EC1}: Lack of finance/Limited financial incentives for new vehicles/ULEVs/public transport/ - Inefficient or absent fiscal measures for supporting EE
			b_{EC2}: Limited infrastructure investment (road/train/cycling) – for public transport
			b_{EC3}: Low purchasing power of citizens/Financial crisis
			b_{EC4}: High cost/Low cost competitiveness of electric vehicles - High cost of batteries for electric vehicles
			b_{EC5}: Payback period of fuel efficient vehicles
			b_{EC6}: Negative role of Investment schemes/employee benefits encourage transport EE
	IN		b_{IN1}: Administrative fragmentation and lack of integrated governance
			b_{IN2}: Transport EE on the Government Agenda/priorities
			b_{IN3}: Barriers to behavior change due to problems with infrastructure/public transport services (Inefficient urban/public transport infrastructure and planning/ Undeveloped cycling/walking infrastructure/ Lack of support for rail transportation/Limited rail infrastructure/ Undeveloped infrastructure for recharging of EV)
			b_{IN4}: Lack or limited policies to support behavior change on specific transport issues (Lack of national strategy for bike and pedestrian mobility/ Limited policy on freight efficiency/city logistics
			b_{IN5}: Limited/complex funding in urban public transport
			b_{IN6}: Barriers to behavior change due to no policy support to technological issues/research needs (Immature status of developing technologies for EVs/ULEVs - Range of distance travelled between charges for EVs)
			b_{IN7}: Contradicting policy goals (particularly road/car-oriented planning)

Table 3. AHP matrix for pair-wise comparisons.

Group of barriers	S-C-E	EC	IN
S-C-E	1	A_{12}	A_{13}
EC	$A_{21} = 1/A_{12}$	1	A_{23}
IN	$A_{31} = 1/A_{13}$	$A_{32} = 1/A_{23}$	1

Table 4. Relative importance between comparisons of AHP method.

Intensity	**Definition**	**Explanation**
1	Equal importance	Two barriers contribute equally to the goal
3	Moderate importance	Experience and judgement slightly favours the one over the other
5	Essential or strong importance	Experience and judgement strongly favours the one over the other
7	Demonstrated importance	Dominance of the demonstrated in practice
9	Extreme importance	Evidence favouring the one over the other of highest possible order of affirmation
2,4,6,8	Intermediate values	When compromise is needed

Table 5. Calculations in AHP matrix for the respective Impact factors.

Group of barriers	S-C-E	EC	IN	W
S-C-E	1	A_{12}	A_{13}	$W_{S\text{-}C\text{-}E} = (1/S1 + A_{12}/S2 + A_{13}/S3)/3$
EC	$A_{21} = 1/A_{12}$	1	A_{23}	$W_{EC} = (A_{21}/S1 + 1/S2 + A_{23}/S3)/3$
IN	$A_{31} = 1/A_{13}$	$A_{32} = 1/A_{23}$	1	$W_{IN} = (A_{31}/S1 + A_{32}/S2 + 1/S3)/3$
Sum	$S1 = 1 + A_{21} + A_{31}$	$S2 = A_{12} + 1 + A_{32}$	$S3 = A_{13} + A_{23} + 1$	

Step 3.2: Calculation of weight coefficients for the first level of the AHP tree

The necessary calculations of the AHP method are conducted for the determination of the weight coefficients (W) for each *group of barriers* (first level of AHP tree). The weight coefficients of this level express the contribution of the respective group to the goal. This means in the limitation of efforts for achieving the EE target. Due to this contribution, the calculated weight coefficients are defined as “Impact factors (I)” for the groups of barriers. The procedure is the same for all AHP matrices, differences are due to the different rank of the matrix (see Table 5):

a. Sum of each column (add three numbers in this specific case-level); denoted as Si where i refers to the number of the column;

b. Divide each number of the first row with the respective sum of the column it belongs to (A_{11}/sum of column 1 = A_{11}/S1, A_{12}/S2, A_{13}/S3 etc);

c. Sum up the "n" outcomes of step b (here the three outcomes of step b);

d. Divide them with n (since there were *n* outcomes) (*n* is the number of columns and rows of this AHP matrix) (here divide them with 3 (three outcomes for step c));

e. The outcome is weight coefficient for group 1 of barriers (located at row 1, column n+1 or a separate column) (sub-groups or barriers in the next levels);

f. Repeat for the second row the steps b, c, d, e;

g. Repeat for the next rows the steps b, c, d, e;

h. Check if each weight coefficient fulfills the condition $0 < W < 1$;

i. Check if all together, the weight coefficients, sum up 1 (here the three calculated ones).

Step 3.3: Calculation of the consistency test

Values derived from step 3.2 are tested – before being used - for their consistency following the Saaty approach which requires the calculation of the random ratio of consistency (CR*) of the respective AHP matrix.

First, the consistency index (CI) is calculated as

$$CI = \frac{\lambda_{max} - n}{n-1} \qquad (1)$$

where: λ_{max} is the maximum eigenvalue of the matrix and n is the rank value of the matrix.

Then, the random ratio of consistency (CR*) is calculated as

$$CR^* = CI/CR \qquad (2)$$

Where: CR is the corresponding mean random index of consistency. CR is 0 for a 2x2 matrix and CR* is not calculated. For the other nxn matrices, CR receives the values of Table 6 (Bongchul K. et al., 2017; Da A. et al., 2014; Ishizaka A., Labib A., 2011; Konidari P., Mavrakis D., 2007; Berritella M. et al., 2007).

A matrix is consistent (outcomes reliable) if CR* < 0.10, otherwise, the matrix is not consistent and its CR* value should be adjusted. This is done by re-assigning intensities and checking the importance of one object (here for the group of barriers) over the other.

The calculation procedure using the respective AHP matrix is (here Table 5 turns into Table 7):

a. Multiply the first cell of the first row with the first weight coefficient (final matrix of step 3.2), the second cell of the first row with the second one, the third cell of the first row with the third weight coefficient) etc;

b. Sum the products and divide by the first weight coefficient. This will be A1;

c. Multiply the first cell of the second row with the first weight coefficient etc;

d. Sum up the products and divide with the second weight coefficient. This will be A2.

e. Repeat the steps a, b for the third row and any other remaining ones respectively.

f. Add outcomes A1, A2, …… An and divide the sum with "n". Here, add outcomes A1, A2 and A3 and divide the sum with number three. This leads to λ.

g. Calculate CI = (λ – n)/(n-1) for the specific AHP matrix.

h. Calculate CR* = CI/CR (CR value from Table 6). Here CR* = CI/0.58 (matrix 3x3) (Table 7).

i. If CR* fulfils the condition 0<CR*<0.10, then the results are consistent.

When CR* = 0 the respective matrix is perfectly consistent. But due to the fact (argument) that decision-makers do not normally make "perfect" judgements, the value is not accepted (Alonso J.A., Lamata T., 2006).

Table 6. Values of mean random index of consistency.

Size of matrix	3x3	4x4	5x5	6x6	7x7	8x8	9x9	10x10
CR	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Table 7. Calculations for λ of Table 5.

Group of barriers	S-C-E	EC	IN	Outcomes using AHP matrix and its W.
S-C-E	**1** * W_{S-C-E}	$\mathbf{A_{12}}$ * W_{EC}	$\mathbf{A_{13}}$ * W_{IN}	$A1 = (1* W_{S-C-E} + A_{12} * W_{EC} + A_{13} * W_{IN})/ W_{S-C-E}$
EC	$\mathbf{A_{21}}$ * W_{S-C-E}	**1*** W_{EC}	$\mathbf{A_{23}}$* W_{IN}	$A2 = (A_{21}* W_{S-C-E} + 1 * W_{EC} + A_{23} * W_{IN})/ W_{EC}$
IN	$\mathbf{A_{31}}$ * W_{S-C-E}	$\mathbf{A_{32}}$ * W_{EC}	**1*** W_{IN}	$A3 = (A_{31} * W_{S-C-E} + A_{32} * W_{EC} + 1 * W_{IN})/ W_{IN}$
				$\lambda = (A1 + A2 + A3)/3$

Table 8. AHP matrix for the third level of barriers.

Social Barriers (3rd level)	b_{s1}	b_{s2}	b_{s3}	……	b_{sn}	$\mathbf{W_{sn}}$
b_{s1}	1	A_{12}	A_{13}	……	A_{1n}	$\mathbf{W_{s1}} = (1/S1+ A_{12}/S2+.... A_{1n}/Sn)/n$
b_{s2}	$A_{21} = 1/A_{12}$	1	A_{23}	…..	A_{2n}	$\mathbf{W_{s2}} = (A_{21}/S1+ 1/S2+.... A_{2n}/Sn)/n$
b_{s3}	$A_{31} = 1/A_{13}$	$A_{32} = 1/A_{23}$	1	…..	A_{3n}	$\mathbf{W_{s3}} = (A_{21}/S1+ A_{32}/S2+.... A_{3n}/Sn)/n$
……….	……	…..	…….	1	….	**…..**
b_{sn}	$A_{n1} = 1/ A_{1n}$	$A_{n2} = 1/ A_{12}$	$A_{n3} = 1/ A_{13}$	$A_{n\ n-1} = 1/ A_{n-1\ n}$	1	$\mathbf{W_{sn}} = (A_{n1}/S1+ 1/S2+.... 1/Sn)/n$
	$S1 = 1 + A_{21}+.... A_{n1}$	$S2 = A_{12} + 1 +... A_{n2}$	….		$Sn = A_{1n} + A_{2n} + 1$	

Step 3.4: Calculation of weight coefficients for the second level of the AHP tree

Weight coefficients are defined again, but now for each one of the sub-groups of barriers (“W_S”, “W_C” and “W_E”) (second level) to which the wider group “S-C-E” is divided to. These weight coefficients express the relative importance that each sub-group has as part of the wider group “S-C-E”. The previous steps (3.1 – 3.3) are repeated. The conditions of step 3.1 are used for this level also.

Once the weight coefficients of each one of the sub-groups are calculated (ie W_S, W_C, W_E), then – following previous procedure - their equivalent Impact factor (I) in “limiting the efforts for achieving the EE target” is determined as:

$$I_S = W_{S\text{-}C\text{-}E} * W_S \quad (3)$$

$$I_C = W_{S\text{-}C\text{-}E} * W_C \quad (4)$$

$$I_E = W_{S\text{-}C\text{-}E} * W_E \quad (5)$$

The Impact factor expresses the contribution of the sub-group to the goal of the AHP tree. “Economic” and “Institutional” barriers are not divided into sub-groups.

Step 3.5: Calculation of weight coefficients for the third level of the AHP tree

The previous steps (3.1 – 3.3) are repeated for this level of the AHP tree. Under each sub-group there is a number of identified barriers (Figure 1). Following the described procedure, the AHP matrix for the “Social barriers” and their weight coefficients is that of Table 8.

The AHP matrix is filled through the assignment of the intensities that result from the comparison of the identified barriers (b_{s1}, $b_{s2} \ldots b_{sn}$) against each other by taking into consideration the following conditions (different from those in step 3.1):

- A barrier is more important than the other if the *number of different sources* that refer to it are more than those for the second one;
- A barrier is more important that the other if the *number of sub-sectors* that were linked with it are more than those with the second one;
- A barrier is more important compared to the second one if there are *more difficulties to confront it* (the easier to be confronted the less important it is or if difficulties are encountered in more than one level (local, regional, national) it is more important);
- A barrier is more important compared to the second one if it exists *longer than another* (longer recorded duration of the barrier compared to the other);
- A barrier is more important compared to the second one if the *number of different policy instruments that were linked with it is* higher than those of the other;
- A barrier is more important than the second one if it is identified *as a cross-cutting barrier* (common among two or more different sectors (ie buildings and transport));
- A barrier is more important than another if there are available *expressed preferences of stakeholders for it*.

Calculations are performed for this level following those of step 3.2. Again, the calculated weight coefficients are checked for their consistency (step 3.3). The procedure of this step (3.5) is repeated for the “Economic” and the “Institutional” barriers.

Step 4: Definition and calculation of the Impact factors of barriers

The calculated weight coefficients of the previous step express the importance of each barrier as part of the group or sub-group to which it belongs. The Impact factor of a barrier (I) is defined as the weight coefficient of the barrier that expresses its importance to the goal of the AHP tree.

The Impact factor is calculated as the product of the weight coefficients of each one of the identified

Table 9. Impact factor of barriers for the building and transport sectors.

Type	**Barriers of sector**		**Function**
	Building	Transport	
S	b_{s1}	b_{s1}	$I_{s1} = W_{S-C-E} * W_S * W_{s1}$
S	b_{s2}	b_{s2}	$I_{s2} = W_{S-C-E} * W_S * W_{s2}$
S	b_{s3}	b_{s3}	$I_{s3} = W_{S-C-E} * W_S * W_{s3}$
S	b_{s4}	b_{s4}	$I_{s4} = W_{S-C-E} * W_S * W_{s4}$
S	b_{s5}	b_{s5}	$I_{s5} = W_{S-C-E} * W_S * W_{s5}$
S	b_{s6}	b_{s6}	$I_{s6} = W_{S-C-E} * W_S * W_{s6}$
C	b_{c1}	b_{c1}	$I_{c1} = W_{S-C-E} * W_c * W_{c1}$
C	b_{c2}	b_{c2}	$I_{c2} = W_{S-C-E} * W_c * W_{c2}$
C	b_{c3}	b_{c3}	$I_{c3} = W_{S-C-E} * W_c * W_{c3}$
C	b_{c4}	b_{c4}	$I_{c4} = W_{S-C-E} * W_c * W_{c4}$
E	b_{E1}	b_{E1}	$I_{E1} = W_{S-C-E} * W_E * W_{E1}$
E	b_{E2}	b_{E2}	$I_{E2} = W_{S-C-E} * W_E * W_{E2}$
E	-	b_{E3}	$I_{E3} = W_{S-C-E} * W_E * W_{E3}$
E	-	b_{E4}	$I_{E4} = W_{S-C-E} * W_E * W_{E4}$
EC	b_{EC1}	b_{EC1}	$I_{EC1} = W_{EC} * W_{EC1}$
EC	b_{EC2}	b_{EC2}	$I_{EC2} = W_{EC} * W_{EC2}$
EC	b_{EC3}	b_{EC3}	$I_{EC3} = W_{EC} * W_{EC3}$
EC	b_{EC4}	b_{EC4}	$I_{EC4} = W_{EC} * W_{EC4}$
EC	b_{EC5}	b_{EC5}	$I_{EC5} = W_{EC} * W_{EC5}$
EC	b_{EC6}	b_{EC6}	$I_{EC6} = W_{EC} * W_{EC6}$
EC	b_{EC7}	-	$I_{EC7} = W_{EC} * W_{EC7}$
IN	b_{IN1}	b_{IN1}	$I_{IN1} = W_{IN} * W_{IN1}$
IN	b_{IN2}	b_{IN2}	$I_{IN2} = W_{IN} * W_{IN2}$
IN	b_{IN3}	b_{IN3}	$I_{IN3} = W_{IN} * W_{IN3}$
IN	b_{IN4}	b_{IN4}	$I_{IN4} = W_{IN} * W_{IN4}$
IN	b_{IN5}	b_{IN5}	$I_{IN5} = W_{IN} * W_{IN5}$
IN	b_{IN6}	b_{IN6}	$I_{IN6} = W_{IN} * W_{IN6}$
IN	b_{IN7}	b_{IN7}	$I_{IN7} = W_{IN} * W_{IN7}$
IN	b_{IN8}	-	$I_{IN8} = W_{IN} * W_{IN8}$
	The sum of all these barriers fulfils the condition: $\sum_{i=1}^{27} I_i = 1$		

barriers (b), in the relevant groups and subgroups, based on the outcomes of the previous steps and the mathematical equation is as follows:

$$I = W_G * W_{S-G} * W_b \qquad (6)$$

where

I is the Impact factor of a barrier towards the goal of the AHP tree;

W_G is the weight coefficient of the *Group of barriers* to which the sub-group belongs;

W_{S-G} is the weight coefficient of the *Sub-Group of barriers* under the respective group of barriers;

W_b is the weight coefficient of the barrier under the sub-group to which it is classified and expresses the importance of the barrier compared to the other barriers of the same sub-group.

The same procedure and mathematical expression is applied for all barriers of the third level.

For the barriers, that are not classified in sub-groups, the Impact factor is calculated as

$$I = W_G * W_b \qquad (7)$$

All calculated Is do not have measurement units as they express the contribution of the barrier in not achieving the EE target ie the ratio scale in limiting efforts for achieving the EE target. The values of these Is range from 0 to 1, ie $I \in (0,1)$. Table 9 shows the sets of barriers for the building and transport sectors and their calculated impact factors. The numerical outcomes of the impact factors depend on the judgement of the user after applying the respective steps.

Step 5: Linkage of Impact factors of barriers with technologies and policies

EE technologies or practices are promoted - depending on national needs and priorities -through implemented policy instruments. Their penetration is affected by a set of linked barriers.

The Total Impact factor (TI) of barriers is calculated as the sum of all the Impact factors of the barriers linked with the specific EE technology or practice ie:

$$TI = \sum_{i=1}^{n} I_{Si} + \sum_{j=1}^{k} I_{Cj} + \sum_{a=1}^{m} I_{Ea} + \sum_{b=1}^{q} I_{ECb} + \sum_{d=1}^{r} I_{INd} \qquad (8)$$

where

n, k, …, r refer to the maximum number of the relevant barriers linked to the technology/practice under consideration. Each one of these maximum numbers fulfils the condition of being less than the total number of the barriers categorized under the respective group or sub-group (steps 1 and 2).

Equation (8) concerns the TI of barriers for only *one* EE technology or practice. The same equation is applied for calculation of the TI of barriers linked with an implemented policy instrument for EE.

The TI_{ol} of barriers for a *set* of EE technologies/practices is calculated applying the same rationality. The Impact factors of all barriers for all technologies are summed up. The Impact factors for barriers that are encountered for two or more technologies/practices are inserted only one time in the calculations (for avoiding duplication of the same impact factor).

Step 6: Incorporation of the Total Impact factors in the forward-looking EE modeling

The Impact factors (I) and Total Impact factors (TI) define the negative impact on the set of input drivers (or the defined EE target) in the frame of the forward-looking EE analysis. Consequently, the difference between the initially set value and the new one that incorporates Impact factors (I) and Total Impact factors (TI) defines the deviation created by the end-user's behavior.

For reducing this deviation, there are various options derived from the optimum combination of modified inputs, leading to a number of improved scenarios.

Step 6.1: Defining the deviation of EE targets due to behavioral barriers

The EE target is usually expressed by a percentage (±p%) of/about a specifically defined amount and is to be achieved until a defined target year. The numerical value of p% depends on the scenario and whether it concerns a country, region, municipality or sector/sub-sector (if the target concerns the tertiary or the road sub-sector) or even a specific housing type (if the examined sector is the building sector).

This specifically defined amount may refer to the: i) primary/final energy consumption; ii) penetration rates of EE technologies and iii) energy intensity. The latter is expressed in: i) MWh/m^2 or kWh/m^2 for the whole building sector or per any housing type (existing single-family house - housing type 1, existing multi-family building – housing type 2 etc) (Sustainable Energy Authority of Ireland, 2016); ii) tonnes of oil equivalent (toe) per tonne-km for the freight sub-sector and in toe per passenger-km for the passenger sub-sector[17].

The user assumes that a set of barriers affects the defined amount through the use of one EE technology (or the implementation of a policy instrument for supporting this technology). The impact of barriers leads to a new percentage, p_b (in %), which is calculated as

$$p_b = \pm p * (1 - TI) \quad \text{or} \quad p_b = \pm p * (1 - TI_{ol}) \qquad (9)$$

where TI is the Total Impact factor of all barriers linked with this one EE technology/action that is used for achieving the expected EE target and TI_{ol} the Total Impact factor linked with a set of EE technologies/actions for the same purpose.

The value of TI or TI_{ol} depends on the scenario and whether it concerns the whole sector or a specific sub-sector (residential or tertiary of the building sector) since these two elements define the final number of barriers linked with the assumed EE technology/practice.

The difference between the calculated amounts of p_b and p defines the deviation between the set target (ideal) and the target due to the existence of barriers (realistic). A number of scenarios can be developed for reducing this deviation.

Three cases encountered in forward-looking EE modeling about EE targets are examined for demonstrating how equation (9) is applied for specifically defined amounts used in EE targets (quoted in National Energy Efficiency Action Plans[18] for the European Union or National Determined Commitments[19] for the United Nations Framework Convention on Climate Change).

Case 1: EE targets about Primary or Final Energy Consumption

For this case, the aforementioned defined amount refers to Primary or Final Energy Consumption or energy intensity. The same rationality is applied for all these terms of EE targets. The following equations will use the Final Energy Consumption.

The *Final Energy Consumption with the use of a specific EE technology*[20] *for the reference year (which is denoted as 0) is* F_o. A new target about energy efficiency usually refers to a target year and is a percentage of the final energy consumption of the reference year. The expected/needed reduction in final energy consumption or the expected/needed energy savings for the target year (ES_o) without considering the impact of barriers is expressed as

$$ES_o = F_o * p \qquad (10)$$

While the final energy consumption for the target year without considering barriers will be

$$F = F_o - Es_o = F_o - F_o * p \qquad (11)$$

where p (in %) is the assumed expected reduction. The expected/needed reduction in final energy consumption or the respective energy savings for the target year - ***when barriers (b) are considered*** – after using equation (9) are

$$ES_b = F_o * p_b = F_o * p * (1 - TI) \qquad (12)$$

So, the final energy consumption for the target year, but considering barriers will be

$$F_b = F_o - ES_b = F_o - F_o * p * (1 - TI) \qquad (13)$$

The development of the scenarios aims now to reduce the deviation between the calculated amounts of ES_o (or F) and ES_b (or F_b respectively).

[17] http://www.un.org/esa/sustdev/natlinfo/indicators/methodology_sheets/consumption_production/energy_intensity_transport.pdf

[18] http://ec.europa.eu/energy/en/topics/energy-efficiency/energy-efficiency-directive/national-energy-efficiency-action-plans

[19] http://www4.unfccc.int/ndcregistry/Pages/Home.aspx

[20] such as space heating technology

If a set of EE technologies are used then TI becomes TI_{ol} in equations (12) and (13).

Case 2: EE targets and penetration shares for EE technologies or fuels

The initial share (in %) of an EE technology is denoted for the reference year, 0, as S_o. The share of the technology (in %) for the target year is assumed to be

$$S = S_o + p \quad (14)$$

The expected share of the technology *due to the presence of barriers* (S_b) for the target year, based on equation (17), is calculated as

$$S_b = S_o + p_b = S_o + p*(1- TI) \quad (15)$$

Minimizing the difference between S and S_b defines the range of scenario outputs derived due to improved assumptions for confronting barriers.

Case 3: General EE targets

A general EE target is set usually when there is lack of reliable and detailed data about the share of energy sources, types of energy uses etc. The achievement of such a general target is assumed to be accomplished without specified penetration shares or breakdown shares for sectors/sub-sectors; just assuming that it will be achieved through the adoption of available EE technologies.

The scenario developer then proceeds by: i) assuming the use of all available EE technologies for achieving this general EE target (knowing that they are indeed used, but with no official data about their shares, energy consumption etc); ii) selecting a specific set of them based on official documents (such as National Energy Efficiency Action Plans).

The final energy consumption for the target year will be

$$F_b = F_o – ES_b = F_o - F_o*p*(1- TI_{ol}) \quad (16)$$

Where TI_{ol} refers to the Total Impact of barriers on assumed EE technologies (all or selected as aforementioned) for the developed scenario. Common barriers are inserted only once in the calculations. Similar function is used for primary energy consumption or any other type of EE target.

Conditions for all cases

The following conditions complement the previous discussion and are used as check points for the assumptions of the developed scenarios.

First condition: $0 < TI < 1$ and $0 < TI_{ol} \leq 1$.

Out of the 27 barriers for the building or the transport sector (Tables 1 and 2 – Step 1), not all of them are assumed to be linked with only one EE technology, so TI is not equal to 1. If TI was equal to 1, then

$$p_b = \pm p * (1 – TI) = \pm p * (1 – 1) = 0 \quad (17)$$

This means that the EE target is not achieved due to the presence of barriers. For the examined case, this limits completely the achievement of the EE target since it results to $ES_b = 0$ (no energy savings), $S_b = S_o$ (no penetration), $F_b = F_o$ (the final energy consumption remains as it is). This situation requires the re-examination of the assumption adopted in the developed scenario.

The mapped barriers of step 1 include barriers for all available EE technologies and policies. Since the two sets (Tables 1 and 2) are universal not all of these barriers are linked with only one specific EE technology or practice. There are barriers that do not concern the used EE technology of the developed scenario. Also, not all of these barriers are mapped for only one examined case (whether this is country, national sector etc). If the condition is not fulfilled then a check is performed so that TI<1.

Second condition: $TI_{ol,new} < TI_{ol, old} <1$.

If one of the barriers is considered of being overcame sharply, this means that due to a new policy package of measures, its respective Impact factor will be equal to 0 starting from the year of implementing the policy package. The $TI_{ol,new}$ of all the rest barriers is calculated, the index "new" refers to the new set of barriers. $TI_{ol,old}$ refers to the Total Impact of the barriers before the aforementioned change (old set of barriers). The new percentage for the defined amounts is calculated as:

$$p_{b,\,new} = p^{*}\,(1- TI_{ol,\,new}) \tag{18}$$

with $TI_{ol,new} < TI_{ol,\,old} < 1$ and $p_{b,new} > p_{b,old}$.

Step 6.2: Calculation and optimization of the set of input drivers

The development of scenarios for reducing deviations is based on selecting EE technologies and barriers whose impact factors will be reduced.

Selecting suitable combination of EE technologies

The scenario is developed by assuming the use of: i) specific technologies out of a set of available ones (random selection or based on national strategies) or ii) the best combination of them (selection based on impact factors). The selection of the appropriate technologies out of a set of available ones for achieving the expected/assumed EE target is very difficult – in some cases not possible - due to the large number of combinations $\binom{m}{k}$ referring to the exploitation of k out of a set of m technologies. The combination of technologies $\binom{7}{2}$ and $\binom{7}{3}$, results to 21 and 35 respectively. All these combinations cannot be examined since only a few will be more feasible and closer to accomplish the EE target compared to the others.

Combinations with the potential to overcome their barriers successfully and achieve the set/expected target are those that need to be preferred and explored. For concluding with these more efficient or suitable ones the following procedure is followed:

Step 6.2.1: Combinations of available EE technologies with the **maximum number of common barriers** are more preferable than the others, because the efforts for minimizing these barriers will affect the penetration of all involved technologies.

Step 6.2.2: Additionally, to step 1, if there are combinations with the same number of common barriers, the more preferable are those with **the lowest Total Impact**, since: i) overcoming the set of these barriers as a group requires less efforts compared to other combinations ii) the barriers of this set will be more manageable in being confronted and will more likely allow to reach easier the set/expected EE target compared to others.

The TI_{ol} of the suitable combination of the EE technologies is calculated and used as described in step 5. If the combinations are more than those intended to be examined, then an upper limit for the Total Impact of the combinations is to be set ($TI_{ol}<a$, with $a\in(0,1)$ theoretically). By this way, only combinations with TI_{ol} lower that the upper limit are selected.

Minimizing the impact factors of barriers

The scenario developer has two options: i) to assume which barriers of the suitable combination exhibit a reduced impact factor or ii) to assume directly – not through a suitable combination of technologies - which barriers are those whose impact factor will be reduced.

For both options the Impact factor of a barrier is reduced by: i) the introduction in the calculations of the respective impact factor of the policy instrument that is assumed to confront it or ii) a mathematical equation that reflects its reduction over time as the result of the socio-economic and policy framework.

The selection of the barriers whose Impact factors are assumed to be reduced leads to modified input drivers and improved scenario outcomes.

Option 1 for minimizing: Using the Impact factor of policy instruments

The Impact factor of a barrier is assumed to be overcame or restricted due to the respective Impact factor of a Policy Instrument (I_p) with $I_p\in(0,1)$. This assumption is based on the approach adopted by scholars in modelling that the introduction of policies overcomes barriers (Rehmatulla N. et al., 2017). This I_p is defined similarly to the Impact factor of a barrier, but expresses the positive impact that the policy instrument has in achieving the defined EE target by supporting the use of an EE technology or practice.

Similar research efforts need to be exerted for calculating these I_p and then for linking each one with the EE technology or technologies that it supports. Calculation needs to be based on research and collection of data and information, different from the one that led to the calculation of the impact factors of barriers.

Equations (17) are formed as

$$p_{b,p} = \pm p * (1 - TI + TI_p) \quad \text{or}$$

$$p_{b,p} = \pm p * (1 - TI_{ol} + TI_{p,ol}) \qquad (19)$$

where $p_{b,p}$ is the resulting percentage for the specifically defined amount after considering barriers and policy instruments linked with one or more EE technologies. TI_p is the Total impact factor of the policy instruments that support the EE technology and confront the barriers linked with it. The TI_p is the sum of the impact factors of all the policy instruments supporting the defined EE target through one EE technology, ie

$$TI_p = I_{p1} + I_{p2} + \ldots + I_{pn} \qquad (20)$$

where n is the number of these policy instruments

Similarly, the $TI_{p,\,ol}$ (in equation (19)) is the Total impact factor of all the policy instruments that support the set of EE technologies used for achieving the EE target.

The reduction in the final energy consumption or the respective energy savings due to barriers and policy instruments are calculated as

$$ES_{b,\,p} = F_o * p * (1 - TI + TI_p) \qquad (21)$$

Then

$$F_{b,p} = F_o - ES_{b,\,p} = F_o - F_o * p * (1 - TI + TI_p) \qquad (22)$$

Option 2 for minimizing: Using linear function for reducing impact factor of a barrier

The function that describes the reduction rate of the Impact factor of a barrier follows that of the change rate (increase or reduction) over time of the primary/final energy consumption, energy intensity, energy savings or of penetration rates. Assuming that this change rate over time is a linear function then the reduction of the Impact factor is calculated as:

$$I_{t,i} = I_{o,i} (1 - (c/15)*t) \qquad (23)$$

where

$I_{o,i}$ is the Impact factor of barrier i in year t=0,

$I_{t,i}$ is the Impact factor of barrier i in year t after the implementation of a policy instrument (or instruments) that addresses it. For any other year than t=0, the $I_{t,i}$ satisfies the mathematical condition $I_{t,i} < I_{o,i}$.

The initial conditions that define this final form, starting from the general one, $I_{t,i} = a*t + b$, are:

- For year t=0, the $I_{o,i}$ is already calculated following steps 1-4 of the methodology, and $I_{t,i} = I_{o,i}$.
- For year t = 15 (in 2030), the assumption is that $I_{o,i}$ is to be reduced by c (20% < c < 80%). This reduction means that barrier i, has a lower contribution in preventing the achievement of the EE target. The 20% reduction was selected as an indicative value because: i) the mapping of the barriers (Step 1, Tables 1 and 2) showed that the majority of them remains important for several years despite the implementation of policy instruments; ii) there are estimations of 20% higher achievement of the EE target after the implementation of behavioral measures (UNEP, 2016). Additionally, depending on the measure or driver the abatement of a barrier may range from 5 to almost 80% (Trianni A. et al., 2016). Whether the assumed upper and lower limits capture sufficiently the reduction of the I or not, this requires further research (HERON, 2016).
- The year 2030 was selected due to its importance for: i) the Paris Agreement and the ii) European Union. The efforts under the Paris Agreement intend to lead to a projected level of 55 gigatonnes in 2030, while the EU aims to achieve at least 27% improvement in energy efficiency for year 2030 compared to

projections[21]. This corresponds to a time interval of 15 years (starting from 2015).

- Based on these initial conditions, the calculations resulted to a = - c/15 and b = $I_{o,i}$. This linear function is used for each barrier whose impact factor is assumed to be reduced.

TI and TI_{ol} are calculated using the previous equations and the calculated $I_{t,i}$ wherever it is needed according to the assumptions of the developed scenario.

For reduction by 20% in year 2030, equation (23) becomes

$$I_{t,i} = I_{o,i} (1 - (0,2/15)*t) \quad (24)$$

In the case of the most suitable combination of technologies the minimization of the impact factor of a common barrier is divided equally among the involved technologies. The outcomes are inserted in the forward-looking EE model as described previously.

3. Outcome of methodology

The methodology allows the development of various EE scenarios that incorporate the end-users' behavior. Through the selection of the most suitable combination of EE technologies and the minimization option, different deviations from the set/expected EE target are achieved. The scenario with the lowest deviation is not necessarily the most promising one for the examined case. These scenarios need to be assessed using the multi-criteria evaluation method AMS, that will rank them based on their overall performance against three main criteria (environmental performance, political acceptability, feasibility of implementation). The evaluation outcome shows the scenario that: i) considers end-users' behavior; ii) exploits the most suitable combination of EE technologies and iii) has the most promising policy package in achieving the set EE target.

4. Conclusions

The developed methodology through its six steps leads to: i) the quantification of the barrier impact based on qualitative information; ii) the incorporation of end-users' behaviour in forward looking EE modelling; iii) the development of EE scenarios that reflect better the future development of the set/assumed targets. It allows the understanding of: i) which barriers are more important compared to others; ii) the deviation from the set/expected EE targets (primary or final energy consumption, energy intensity or penetration share of an EE technology) due to barriers linked with end-users' behavior; iii) how the minimized impact factor of barriers lowers the deviation from the set/expected EE target.

Steps 1-4 are followed for any sector that is to be examined in forward-looking EE modelling. The sets of barriers were presented in the paper for two important sectors for EE, buildings and transport. An analysis of the final end use of energy in the EU-28 in 2015 shows three dominant sectors: transport (33.1 %), households (25.4 %) and industry (25.3 %)[22]. The user of the methodology may conclude to a different number of barriers as a total or for each group/sub-group, but the AHP tree has the same structure as in Figure 1.

The groups and the sub-groups of barriers are the same among the sectors, but the barriers themselves differ in their titles and numbers per group or sub-group.

With the aim to simplify the AHP procedure, the preferable maximum number for each AHP matrix is 8x8. It will be thus easier and less time consuming for users to have 8 or less barriers to compare each time under an AHP matrix instead of 9 or 10. Additionally, the consistency test will be fulfilled

[21] Similar to the objective of saving 20 % of the Union's primary energy consumption by 2020 compared to projections. (Energy Efficiency Directive – 2012/27/EU, available at: http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32012L0027&from=EN

[22] http://ec.europa.eu/eurostat/statistics-explained/index.php/Consumption_of_energy

easier as well. All identified barriers are either grouped or merged so as to form the respective groups and sub-groups with up to 8 barriers the most for each. If this is not achievable then inevitably the user can have the 9x9 or the 10x10 matrix.

The reliability of the outcomes of the methodology depends on the inputs. The Saaty consistency index is used for securing the acceptable consistency of the judgements across all pairwise comparisons and the validity of the outcomes (Abbas M. S., Kocaoglu D.F., 2016).

A second consistency index – such as that of Pelaez-Lamata (2003) - may be used additionally, leading to higher level of consistency and reliability of the results. Its inclusion as part of the methodology depends on the user requirements. The following disadvantage needs to be considered. If the AHP matrices are larger than 6x6 then the consistency index of Pelaez-Lamata becomes sensitive and more time consuming in being achieved in case that the condition is not fulfilled with the initial inputs of the AHP matrices. These inputs need to be re-examined and re-assigned for fulfilling the condition of the consistency test of Pelaez-Lamata. This procedure lasts much more compared to that of the Saaty approach particularly for rank values of the AHP matrices higher than 6. This was the main reason for not including it in the developed methodology since the size of the AHP matrices can be higher than 6x6 and the majority of the potential users will be having difficulties to proceed and complete the methodology.

The deviation from the set/expected EE target reflects the impact of the barriers in achieving it. The calculated Impact factor along with the proposed combination of EE technologies or practices allows the modeler to select the barriers that need to be confronted and assume how the appropriate means (policy instruments) minimize or eliminate their impact factor. The assumptions for reducing the deviation through the minimization of the selected barriers define the synthesis of the policy mixture that may be adopted.

This methodology under which scenarios for energy efficiency are developed allows also their comparative evaluation so as to understand which one fits better the national needs and may reach the best possible results given the national social, economic and administrative framework.

Acknowledgements

This paper is the detailed and complete version of the short paper that was presented at the 9th International Conference on “Energy and Climate Change”, 12-14 October 2016, Athens, Greece (ISBN: 978-618-82339-5-9).

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Методология включения поведения конечных пользователей в моделирование сценария эффективности энергопользования

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Краткое изложение: Отклонения от выполнения задач энергоэффективности (ЭЭ) объясняются главным образом барьерами, создаваемыми поведенческими схемами конечных пользователей. Методология, основанная на аналитическом иерархическом процессе (AHP), касается расчета и взаимосвязи общих факторов воздействия поведенческих барьеров, продемонстрированных конечными пользователями с входными драйверами в моделировании ЭЭ. Предусмотрены два набора поведенческих барьеров для зданий и транспорта. Комментарии, преимущества и недостатки обсуждаются в выводах.

Ключевые слова: Энергоэффективность, поведенческие барьеры, фактор воздействия, моделирование энергии.

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ISSN: 2529-0940