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GENERATIONAL DEMATERIALISATION OF ENERGY IN THE WORLD ECONOMY: EVALUATION APPROACH FOR SUSTAINABLE MANAGEMENT POLICY

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Several methods and ecological indicators are used in environmental economics to analyse the process of sustainable use of natural resources. These approaches are helpful in measuring and assessing the intensity (efficiency) of products' use and their impact on the environment. However, they do not sufficiently reflect the dynamics and improvements in the achieved outcomes as compared to the population (generation) growth. Moreover, they do not allow always analysing product changes on the world level. Referring to this existing gap, we conceptualise a new approach — product generational dematerialisation (PGD) indicator, measuring product efficiency and population changes in relative values, and use it for investigating the dematerialisation for the world energy sector in the last 35 years. The indicator can be used as a new methodical tool to support and evaluate sustainable management policies on the enterprise, regional, national, and international level as well as for different resources, goods, and services.

Keywords: Energy efficiency; energy production; product generational dematerialisation indicator (PGD indicator); strategic environmental assessment; sustainable development; sustainable management policy.

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Introduction and Problem Setting

According to the US Geological Survey report about the use of natural resources (US Department of the Interior, 2009), the global water use during the past 25 years has remained rather stable, despite the population increase of 30%. This tendency is promising in terms of sustainable resource use. However, the methodology used for this investigation sets limits for analysing the respective years and periods in the time series. According to this methodology, the analysis of water use in the past ten years only would deliver the same results as for the previous 25 years including the population change. This would not be accurate or helpful in establishing trends. Thus, based on such a methodology, the efficiency assessment with regard to water use is inaccurate. This example reveals a need for creation of an indicator/methodology that would depict the level of product efficiency between two selected time periods characterised by different population growth. The possibility to assess higher product efficiency (called dematerialisation) and/or lower product efficiency (called materialisation) would help to design a more effective sustainable development policy.

The idea of sustainable development refers to human activities in the field of environment, society and economy. As claimed by Carter (2004), humans are morally obliged to reduce the risk that our environmentally destructive behaviour poses for our well-being.

This obligation can be fulfilled by means of several approaches. Many internationally acknowledged methods in the field of sustainable management policy are known, supporting the reduction of an excessive depletion of natural resources. All of them have the aim to improve product efficiency (i.e., dematerialisation) by means of, for example, cleaner production, eco-innovations, eco-design, low carbon economy, or industrial ecology. All of these concepts, as well as other approaches, such as Life Cycle Assessment (LCA), factor X, ecological rucksack, or Material Flow Analysis, were developed in order to enhance the knowledge about changes in product efficiency. Thus, these ecological concepts allow measuring the intensity of product impact on the environment and help to draw conclusions for decision-making. However, concurrently, the indicators derived from the mentioned approaches do not reflect the dynamics of the achieved improvements compared to the population (generation) growth because of their methodology restrictions, limitations, assumptions, focus or objectives. Therefore, the outcomes on dematerialisation achieved from the analyses by implementing these indicators are not entirely useful and beneficial to the researchers or for regional, national, and world strategic policy purposes.

Relating to this methodological gap in the field of sustainable management policy, we develop a new dematerialisation indicator — product generational dematerialisation indicator (PGD indicator or generational dematerialisation indicator) that allows us to measure and assess in relative values product efficiency with regard to the population (generation) growth. As opposed to the other already existing indicators in the field, the introduced generational dematerialisation indicator allows measuring the scale of dematerialisation, which exceeds the common analyses of changes in the quantity of implemented resources.

The generational dematerialisation indicator measures the scale of change in the use of natural resources versus the scale of change in the population number. However, dematerialisation does not occur due to population increase or decrease. The indicator reflects a way of economic assessment that, in some regard, corresponds with and evolves from the traditional concept of dematerialisation by Cleveland and Ruth (1998), defined as an absolute or relative reduction in the quantity of materials used and/or the quantity of waste generated in the production of a unit of economic output. The generational dematerialisation indicator presented in this paper reflects dynamic changes in production per population (i.e., per capita). The rate of quantity change (calculated on the base of dynamics indices) related to the rate of dynamic changes in production (expressed in relative values) create an added-value of the product generational indicator over other frequently used per capita indicators.

The indicator informs not only about the consumption but also about other indexes, here, the rate of change in consumption in a population. This feature of the indicator makes it distinct compared to other indicators, as it allows making a direct assessment about dematerialisation or materialisation as well as about their range and scope. The traditional dematerialisation indicators which are measured per capita do not represent this benefit, as they inform just about the level of consumption without reflecting the level of an increase or decrease in percent. Yet, this characteristics of the product generational dematerialisation indicator is beneficial for comparative analyses among different goods (expressed in different metric units), as well as for different scales (dimensions), i.e., micro-, mezo- and macroscale.

It should be also stressed that the PGD indicator allows analysing trends in the dematerialisation process, but does not explain the reasons of the processes. In order to answer the question about the reasons, other research approaches would need to be considered, particularly from the field of strategic analysis. Additionally, other external factors and past market events would need to be considered in such an analysis, i.e., oil crises, market recessions, etc. As this question is beyond the scope and objective of our study, we do not investigate it in detail in this paper.

The paper is structured as follows. In Sec. 2, the concept of dematerialisation is presented. Section 3 describes the methodology used and the calculation of the product generational dematerialisation indicator. In Sec. 4, the analysis on generational dematerialisation in the energy sector in the world economy is discussed. Finally, conclusions, recommendations and challenges for the further research are formulated in the last section.

Dematerialisation: Theory and Concept

The understandings, as well as traditional definitions, of dematerialisation are highly differentiated in the scientific discussions. The holistic approach of the (absolute) dematerialisation, promoted by most scientists, refers to a decrease of all material inputs in the economy. The dematerialisation indicators have similar general assumptions. The assumptions of the generational dematerialisation indicator presented in this paper correspond with the general assumptions for all dematerialisation indicators in the management theory and practice. However, the generational dematerialisation indicator has a different character, since it is focused on one product only (energy sector), thus reflecting a relative change of a ratio between the energy input and population growth.

Moreover, it should be mentioned that if we were to consider the holistic approach, all other materials would need to be taken into account in order to include the energy estimates in a broader context of the dematerialisation debate. The approach presented in this paper has the aim to create a universal indicator.

In order to avoid word confusion, we introduce just one phrase: “product generational dematerialisation” which can be understood, in the case of energy, as “generational efficiency improvements in the world energy production”.

The research studies discussed in the literature are focused rather on only one or several materials than on all materials used in an economy. For example, Behrens *et al.* (2007) analysed time trends in domestic extraction of four material groups: fossil fuels, metals, industrial and construction minerals, and biomass. In turn, according to Sun (2001), dematerialisation/materialisation is the real change of the energy use in one year, if this change is less/more than the trend based on the level of a given base year changes, and only if this tendency occurred throughout the whole observation period. A similar viewpoint is presented by Nowak (2006), who stated that the dematerialisation is a quantitative decrease of deployed natural resources. Tapioa *et al.* (2007) claimed that dematerialisation is the reduction of carbon intensity in the energy production process and in the transport sector. Carolan (2004) says that the digital revolution is the “dematerialisation” of production and consumption because it is less consumptive with regard to resources than other forms of production. When considering transformational effects of Information and Communication Technology (ICT) on the environment, Reisch (2001) defined dematerialisation, e-substitution, green marketing, ecological product life optimisation, etc. as a way to increase consumption efficiency (see, Plepys, 2002). According to Høyer and Næss (2001), dematerialisation is a result of recycling, while according to Kander (2005), Grubler (1998), Ekins (2000) and Bierter (2008), dematerialisation appears when the productivity of natural resources is increasing. This is when, e.g., one kilogram of material produces one kWh of energy, and from one product, so many services can be produced and for as long time as possible (Bierter, 2008). Thus, dematerialisation refers to the absolute or relative reduction in the quantity of materials used and/or the quantity of waste generated in the production of a unit of economic output (Cleveland and Ruth, 1998). Similarly, Schütz and Steurer (2001) defined dematerialisation as absolute or relative reduction in the use of material and energy per unit of value added or output. According to Sonnenfeld (2000), the substitution of high-technology for raw material inputs or substitution of recycled or recovered waste for virgin raw materials is recommended. As dematerialisation is linked to decoupling of environmental harms from the material production (Tapioa *et al.*, 1995, acc. to Ausubel, 1995; De Bruyn, 2002), it is also characterised as increasing eco-efficiency (Tapioa *et al.*, 2005, acc. to Schmidt-Bleek, 2000). According to Behrens (2004), dematerialisation was assessed as the preventive strategy for environmental challenges unleashed by an increasing scale of the economic subsystem. This strategy recognises that it is not only the environmental pressure of specific pollutants, but also the enormous quantity of energy and material flow inputs to the economic subsystem, that pose the central ecological problem (Nachhaltigkeit, 2001). Because of this, dematerialisation requires a considerable reduction of land, energy and materials consumption in order to be sufficient (Behrens, 2004).

Despite several existing indicators for measuring product efficiency, Labuschagne *et al.* (2005) pointed out that due to insufficient statistical data, additional research surveys in this area are necessary. Moreover, OECD (2008) called for the development of indicators that reflect waste minimisation efforts more comprehensively, as well as for the development of appropriate measures and approaches to evaluate the energy efficiency.

The problem of the increasing energy production has become a global issue in recent years. The International Energy Agency (IEA, 2007)) estimates that $22 trillion will be needed for new investments to meet the expected global energy demand in the next two decades (National Research Council of the National Academies, 2008). In 2009, IEA (2009) projected an increase of the world primary energy demand by 1.5% per year between 2007 and 2030, from over 12,000 million tons of oil equivalent (Mtoe) to 16,800 Mtoe, which makes 40% increase in total. Moreover, according to the European Climate Foundation (2010), energy consumption in the European Union amounted to 3,354 TWh/year in 2006 and the demand is estimated for 4,900 TWh/year in 2050.

In the report "2020 vision: Saving our energy", the European Commission (2007) stated that Europe is squandering its energy resources. The consequences are: damage of the environment, climate change, and financial expenses. However, if everyone would contribute, Europe could save a fifth of its annual energy consumption by 2020; compared to "business as usual" (European Commission, 2007). As a result, the sustainable energy policy can be followed, which is important especially in the context of growing population and numerous problems with the production of large energy quantities. Also with regard to environmental issues, the intensified extraction of fossil fuels can result in higher carbon dioxide (CO_2) emissions and, simultaneously, induce climate changes.

Several governmental and scientific reports discuss the growing intensity of energy consumption in the last years. This tendency is quite obvious, given the population growth and the resulting increase of the energy production. According to World Business Council for Sustainable Development (WBCSD, 2004), the energy demand could double or triple by 2050 as a result of the population growth and of the economic expansion in some developing countries overcoming the poverty problem.

The issue of energy demand can take a different form when analysing the changing intensity of energy production caused by the increased world population, especially in long term. In such a case, the influence of the global sustainable management policy and its regulations on the decrease of the energy production can be easily assessed.

In this paper, the change in the energy production (and energy efficiency) is investigated in the context of total energy consumption. Accepting the existing theories mentioned above, we propose a new way of calculating energy consumption — product generational dematerialisation indicator.

The generational dematerialisation is a new and multipurpose approach as compared to traditional dematerialisation. While considering the generation (population) growth, the concept of "generational" dematerialisation allows a dynamic analysis of product efficiency linked to the population quantity. As the PGD indicator denotes ex-post changes of product dematerialisation, it can be used as a reference tool for benchmarking.

Using the generational dematerialisation indicator, comparisons between different enterprises, units, countries, and commonwealths in terms of environmental declarations of goods and services can be done. These comparative analyses are possible because the consumed quantity of resources (the quantity of implemented resources) is expressed in relative values and simultaneously does not depend on the way of its calculation (which can determine final results in a case of price relations characterised by unstable purchasing power).

The conceptualisation and presentation of a new dematerialisation indicator in this paper also clearly refers to the expectations expressed by the Strategic Environmental Assessment (SEA). According to Arce and Gullon (2000), the development of evaluation indicators, criteria, and methodologies are necessary for the successful applicability of Strategic Environmental Assessment, while the establishment of sustainability indicators will consecutively contribute to progress in this process.

Moreover, the implementation of the PGD indicator makes it possible to diminish the existing barriers mentioned by Hoekstra and Van Den Bergh (2002), while referring to comparative investigations. The authors claimed that several methods that are capable of processing physical information, such as Life Cycle Assessment (LCA), Material Flows Analysis (MFA), and Material-Product Chain Analysis (MPCA), are inapplicable for economic analyses on the national level. However, in the case of MFA, practical implementation activities proved that its applicability is also available on the national level (Hinterberger *et al.*, 2003).

However, using the generational dematerialisation approach, strategic assessments can be made about changes of societal attitudes in terms of consumption (exploitation) of natural resources. The value of this indicator denotes not only social behaviour but also indicates the effectiveness of implemented sustainable management policies. Thus, the presented indicator can be used as a methodological extension of the already existing methods for creating different policy scenarios as well as for policy design and updates in regional or international management policies.

In order to highlight methodological possibilities of the presented PGD indicator, we introduce a quantitative analysis of energy efficiency in the world economy from 1972 to 2006. We present the energy dematerialisation in the world economy and define the energy generational dematerialisation indicator as a difference between the dynamics of the world population and the dynamics in energy production.

In reality, the quantities of the energy production are mostly the same as the energy consumption because the produced energy is almost always totally consumed by producers during the production process, transformations and by final consumers. The possible deviations between the energy production and consumption in the statistics result from different methodology assumptions. Because of this, many authors (e.g., Pilavachia *et al.*, 2008) predict the future energy consumption by relying upon the data for the energy production in previous years. According to this common methodological proceeding, we use data for energy production in the context of the published research investigations and we assume in our analysis that the energy production is equal to the energy consumption.

By applying the PDG indicator for the energy production, and because of missing statistical data, we do not differentiate between different energy resources (renewable and nonrenewable). In this paper, the production refers to the quantities of fuels extracted from the ground after the removal of inert matter or impurities (e.g., sulphur from natural gas) (OECD, 2009a).

In the previous and current literature, the change in the quantity of the consumed resources is usually depicted by indicators that do not convey the production (consumption) changes of resources, referred to the population consuming these resources. For example, the study by Cleveland and Ruth (1998) quotes different calculations of consumption per capita in average material use intensity (see also, Radcliffe, 1976; Larson *et al.*, 1986; Jänicke *et al.*, 1989, 1997; Rogich, 1993). It is naturally possible to conduct by-calculations (*de facto* additional and auxiliary calculations relative to traditional dematerialisation indicators). However, their effects for the economy and sustainable management policy purposes have not been sufficiently established so far. The reason is that indicators are missing that would depict just this single matter (i.e., combination of dynamics of resource use ((production)) and of population growth, as conceptualised in this paper). Such methodology, or an indicator and its calculation, would accelerate and facilitate comparative analyses in the future, not only because of the simplicity in handling it but also due to the possibility of much broader implementation. Moreover, the relative values of this indicator would allow cross-analyses among all potential sectors and products.

Another argument for the innovative character of the presented generational dematerialisation indicator can be the possibility of trend visualisation. The model proposed in this paper facilitates the understanding of the rules of generational dematerialisation as well as of the generational materialisation among societies. It can be used as a simple tool in management policies and projects on all educational and managerial levels.

Using this indicator, we explore annual intensity of the energy production in the world economy for the time period 1972–2006. On this basis, we discuss consequences for future trends in energy consumption as well as chances for successful development of the current sustainable management policies. Hence, we introduce the PGD indicator as an alternative to other indicators or a complementary tool in Strategic Environmental Assessment.

Methodology

Several dematerialisation indicators are known in the field of evaluation science and practice. However, they are not commonly acknowledged as evaluation tools. Simultaneously, the need for exploration and development of new dematerialisation indicators is underlined by several scientific deliberations (see, Cleveland and Ruth, 1998; OECD, 2008).

We seek to contribute to the current methodology development by introducing the generational dematerialisation indicator that extends the scale of approaches covered by already-used product performance indicators.

The methodological contribution given with the generational dematerialisation indicator is possible due to its universal character. We use it to demonstrate just one aspect of dematerialisation, i.e., product efficiency. Based on the example for energy sector, the aim of the research is to underpin the overall benefits of the presented indicator and its multi-sectoral character. Simultaneously, in this paper we do not address the holistic approach of generational dematerialisation and, therefore, do not conduct similar calculations for other materials or sectors.

The product generational dematerialisation indicator is calculated in this paper by subtracting the dynamics of production from the dynamics of the world population, according to the algorithm: $\text{PGD} = \Delta$ *world population* $-\Delta$ *world production*.

The term "generational" refers to the analysed population. However, depending on the scale of conducted analyses, the size of population can differ, as can the area covered.

The dynamics presented in this paper were calculated upon the volume of the produced energy and were translated, after transposition, into relative values.

In the process of the indicator development, five steps have been conducted: (1) Definition of the energy production, (2) Calculation of dynamic effects in the production (consumption), i.e., changes in product quantities between two time periods, (3) Definition of demographic situation in the world, (4) Calculations of dynamic effects in the demographic change, and (5) Calculation of the ratio outcome of demographic and production dynamics.

The positive value of the calculated indicator denotes the generational dematerialisation process, while the negative value indicates the materialisation process (in such a case, the indicator can be called as product generational materialisation indicator).

We investigate dematerialisation process in the energy production on the global world population scale. For this, we calculate a change in the consumption for the given world population in each following year. Thus, the scale of the generational dematerialisation depends not merely on the total energy production but on the energy production consumed by a directly defined population group. This way of measurement was chosen because even if both the total energy production and the population are decreasing at the same time and to the same or similar extent, the energy consumption relative to the population is not changing and therefore, no generational dematerialisation can be observed. As opposed to our interpretation above, the described situation of a decrease in energy production (without considering population changes) would be defined as dematerialisation when using traditional indicators. Additionally, it is important to remember that dematerialisation did not occur due to a consumption increase or decrease alone, but was accompanied by population changes.

For the energy production analysed in this paper, generational dematerialisation is given when the energy production increases slower than the population. By contrast, generational materialisation appears when the increase in the total energy production is faster than the population growth. Both changes (increase/decrease) in the energy production and population are assessed relatively. Assuming the same dynamics of the energy production and the population growth, a balance situation is given (Fig. 1).

The production change reflected with the product generational dematerialisation indicator is expressed in percent, when comparing the indicator values for the world economy from 1972 to 2006. The percentage definition of the indicator allows comparing different goods and units, which again helps to investigate progress towards efficiency improvement in the world energy production and to depict potential changes (increase or decrease) with regard to each kind of natural resources analysed by means of PGD. Therefore, dynamics in the international economies can be easily analysed.

When assessing international activities in the context of a long-term sustainable development management, stimulated among others by the Earth Summit in Rio de Janeiro, the following question should be asked: "Are current world circumstances and international agreements leading to dematerialisation?", in other words, "Does the world sustainable policy induce the increase or decrease of the energy generational dematerialisation?" We define "world sustainable policy" as global political awareness of sustainable development. To answer this question, we use the PGD indicator and verify the hypothesis: "The population growth from

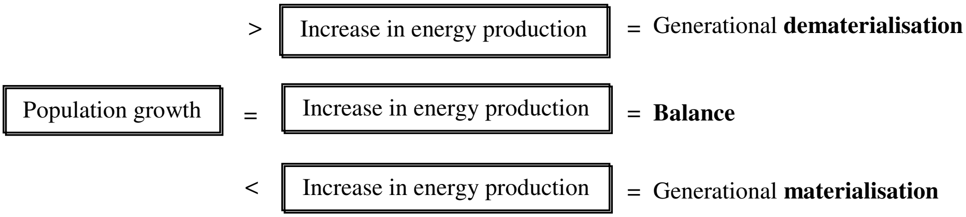

Fig. 1. Concept of the generational dematerialisation and materialisation for energy production. *Source*: Authors' performance

1972 to 2006 induced a global decrease in generational dematerialisation of energy." For this analysis, statistical data were used from US Census Bureau (US Census Bureau, 2008) on the population growth and from OECD (OECD, 2009b) on the energy production (in Mtoe — Million tons of oil equivalent) in the analysed time period.

Results and Discussion: World Energy Generational Dematerialisation

The analyses show a significant unfavourable (for the present civilisation) trend in the world energy generational dematerialisation from 1972 to 2006. The outcomes of the analysis deliver research material for multidimensional deduction process. In this section, we present different ways of the analysis, reflecting the variety of conclusions, interpretation and discussion of the results.

According to the data analysis, the global energy production (consumption) in 2006 was approximately 100% higher than in 1972, whereas in the same period the population increased by about 70%.

The results of the analysis allow us to claim that the generational materialisation of energy in 2006 was nearly 20% larger then in 1972. This means that the world population consumed in 2006 about 20% more energy than 35 years ago. These results cannot be directly compared with other more general indicators that encompass simultaneously several resources, different timelines and values as well as different assumptions. For example, the analysis of four materials (fossil fuels, metals, industrial and construction minerals, and biomass) conducted by Behrens *et al.* (2007) showed that world average per capita extraction dropped from 9.2 tons in 1980 to 8.8 tons in 2002. However, it is important to stress that Behrens *et al.* (2007) show general efficiency of just four materials, not focusing on a single sector. This example reflects the difficulty with comparing similar approaches that differ in the methodological way or basic assumptions even within of one study.

The values of the generational dematerialisation indicator suggest that the world sustainable development policy for encouraging energy efficiency is not as effective to guarantee a balance in terms of the resource use. This occurs because in the analysed time period, the global energy production is mostly larger than the population growth (what is indicated by the negative values of the PGD indicator in the respective years) (Fig. 2).

When analysing the generational dematerialisation and materialisation, an increase of the energy production per analysed population can be noticed in each following year; although regular peaks and valleys are apparent. The energy generational dematerialisation was found to have appeared in the years 1974–1975,

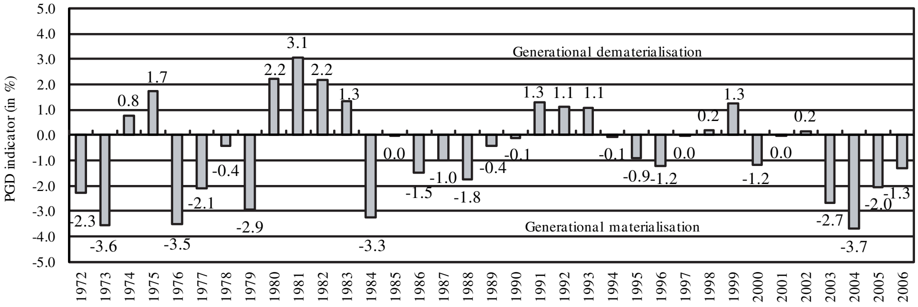

Fig. 2. Generational dematerialisation and materialisation of energy production in the world economy in 1972–2006 (in %).
Source: Authors' calculation

1980–1983, 1991–1993, 1998–1999, and 2002, while generational materialisation in 1972–1973, 1976–1979, 1984, 1986–1990, 1994–1996, 2000, 2003–2006. During these materialisation and dematerialisation periods, the longest sequence of four years of dematerialisation occurred in 1980–1983. The longest energy materialisation lasted consecutively for five years (1986–1990) and for four years in 1976–1979 as well as in 2003–2006.

The frequency of positive and negative indicator values allows us to claim an evident generational materialisation trend in the energy production. The proportion of positive (dematerialisation) and negative (materialisation) values is 12 to 20. Thus, the generational materialisation process was more frequent than the generational dematerialisation in the analysed time period.

The highest energy dematerialisation took place in 1981 (3.1%) and the lowest in 1998 and 2002 (0.2%). The relative balance of the total energy production and population growth occurred in the years 1985, 1997, and 2001. The highest generational materialisation in the energy production was found in 2004 (−3.7%); while the lowest, of −0.1%, in 1990 and 1994.

With regard to regular fluctuations between materialisation and dematerialisation periods, the analysis proves that each dematerialisation period was followed by a materialisation period and vice versa. The summarised relative value of all materialisation periods (−36%) is higher than that of dematerialisation periods (16.4%). This result demonstrates the final outcome of the analysis which means a clear generational materialisation trend (−19.6%) from 1972–2006. Thus, the dynamics in global energy production were dominantly related to the dynamics in population growth in that time period. This allows us to verify positively the hypothesis of this paper and to state that the population growth in the time 1972–2006 induced a global decrease in generational dematerialisation of energy.

For the future sustainable management policy, the analysis results suggest that, in order to diminish the energy consumption by a single world citizen, more and stronger efforts are necessary than those undertaken until now. In this context, a question arises about the future pace of the necessary drivers towards sustainable development. The partial answer to this question is delivered by the generational dematerialisation indicator for the energy production in the last ten years (1997–2006). In this time period, the generational materialisation process was predominant. The summarised value of materialisation amounted to −9.3%, while the average increase of the energy materialisation amounted to nearly −1%. Thus, assuming the increasing tendency at 1% level for the following years, the energy materialisation per population may be 10% higher in 2015 than in 2006. Such a case could be expected in a static market situation. However, in real market situations in world economies, dynamic effects are to be considered. The dynamic changes are visible when analysing the pace of changes in energy production every ten years. By taking into account the last 30 years (1977–2006), the generational dematerialisation indicator amounted to −0.4%, and to −0.5% for the last 20 years (1987–2006). During the last ten analysed years, the average generational materialisation increased extremely rapidly by nearly −1%. If this trend of average changes of about 0.5% per each ten years, appears in the future, then the materialisation is expected to increase by nearly 1.5% in the next ten years (as a result of the present average generational materialisation increase by 1% and the simulated average increase by 0.5%). Provided a *ceteris paribus* situation on the world market, the energy production per population could be expected to increase in 2015 by 15%, as compared to 2006. The presented estimations can help in the future strategic planning in the energy sector and in the ex-ante evaluation of greenhouse gas emissions.

The results correspond with the IEA (2009) simulation that showed a projection of world primary energy demand increase by 1.5% per year between 2007 and 2030.

Moreover, the highest positive and negative values of the generational dematerialisation indicator were estimated for the years 1972–1984. This means that in this timeline, energy consumption behaviour was very unstable. Also, in the years 2003–2006, the negative values of the dematerialisation indicator were higher than in the previous ten years. This means that the dynamics in the world consumption of energy per population were higher than before, which simultaneously shows that the political endeavours to reduce nonrenewable energy consumption were not effective so far.

The years 1985–2002 are characterised by low values of the generational dematerialisation indicator (when compared to the other time periods). This can suggest relatively sustained energy consumption in the world economy.

Additionally, the analysis of the maximal counter-changes of the generational dematerialisation indicator, when comparing two chosen years, shows an extreme shift between the materialisation and dematerialisation that appeared between 1975 (1.7%) and 1976 (−3.5%). This change shows that after a year of a high energy dematerialisation, a materialisation twice as high appeared. It is quite probable that this extreme dynamics was a result of a prior shortage in the energy production. Assuming this interpretation, the overconsumption occurring after the year 1975 can be seen as compensation for the lower energy production per population in the previous years in the world economy.

The concept of the product generational dematerialisation indicator presented in this paper as an example of the dynamics in energy production per population, can be used for analysis of other world relevant questions. Additionally, after slight modifications, it can also be used on micro-, mezo- and macro scale for investigations of development changes for different countries, regions, sectors or even enterprises. The generational dematerialisation indicator applied in this paper refers to one product (energy). However, the analyses conducted with several other resources could deliver new interesting outcomes. The results of the generational dematerialisation indicator can also be helpful for stakeholders conducting comparative analyses for different products on different scales. The application of this indicator can support the following issues:

- Analysing environmental efficiency dynamics,
- Identifying and evaluating the effectiveness of environmental policy among different time periods,
- Facilitating sustainable environmental, energy and development policy creation,
- Identifying consumption areas where the need for diminishing the environmental nuisance is the greatest,
- Showing the pace of introducing resources into economic systems and most dynamic areas, and/or
- Conducting trend and scenario analysis during global and regional crises.

The outlined trend of the energy generational dematerialisation provides a picture of the outlook for natural resource economics. When matching appropriate time periods and regions, it is possible to show the effectiveness for the already realised environmental programs. Thus, the indicator can be used as an ex-post evaluation tool. Besides the benefits of defining previous achievements and discrepancies by implementing the presented approach, the further usage of this indicator can deliver more detailed and sophisticated information on future challenges in different branches, sectors and for different products and regions.

Conclusions, Recommendations and Outlook

Dematerialisation is one of the most effective strategies, when considering the optimal resource allocation (see, Plepys, 2002). This statement can be confirmed in the context of the necessity for new policies that do not hinder innovation but endorse technologies that most effectively promote sustainable economic growth (Plepys, 2002).

The research presented in this paper extends the previous analyses on dematerialisation in energy production by delivering an additional quantitative approach in the field of environmental management and planning. Furthermore, it can be a valuable tool in Strategic Environmental Assessment, useful for regional and global management policies. Using the generational dematerialisation indicator, the results show that the global energy production per population in the world economy is about 20% larger nowadays than 35 years ago. Moreover, the energy consumption per population increased during the last 10 years (1997–2006), which proves the average generational materialisation process of nearly 1% annually for the next 10 years.

If the trend of the average increase by about 0.5% every ten years appears in the future, (so materialisation would increase by nearly 1.5% between 2006 and 2015) then, provided *ceteris paribus*, the energy production per population can be expected to increase by about 15% in the next ten years as compared to 2006.

In the years 2003–2006, the negative values of the PGD indicator were higher than in the previous ten years, which shows that the world population consumed on average more energy than in the previous years.

As a result of the examination conducted in this paper, the hypothesis was positively verified, stating that the population growth from 1972–2006 correlated to a global decrease in generational dematerialisation of energy. This clearly shows the necessity to improve the effectiveness of the current energy production from fossil fuels in the future and/or greater investments in new technologies like renewable resources. Taking into consideration the current potential in the energy sector, we assume that the question is not the quantity of the energy used but rather the energy production structure. If most of the energy produced in the world economy would be delivered from renewable resources, the concerns related to CO_2 pollution and climate change would be less dire.

The presented analysis has the aim to verify the usefulness of the generational dematerialisation indicator as a methodological instrument for more effective sustainable management and to stimulate further development of this research. It shows the materialisation and dematerialisation process, exemplifying the world energy sector. However, the application of the PGD indicator can be used also on enterprise, household, regional, national and international scale as well as for each type of resources, products or services, depending on the data availability. Additionally, the presented research for the energy sector reveals several questions that can be of interest for future studies on the product generational dematerialisation and on comparison analysis for fossil fuels and renewable energy sources (e.g., wind, hydro, solar, geothermal energy, biofuels of first, second and third generation). However, long term analysis can be more complicated due to missing data on renewable energy in the respective countries. A comparative analysis of the energy generational dematerialisation between different countries allows us to assume relevant results. It could also be very helpful for enterprises and governments in the creation process of strategic development plans for economic crises. Additionally, based on the detailed analyses of the dematerialisation indicator, trend maps can be created that would allow analysing ex-post generational dematerialisation and would help to formulate suitable activities and ex-ante investigations for the future. In addition, the knowledge of the past occurrences would also be helpful in assessing accuracy and effectiveness of prior plans and programs on the national and international levels. However, it needs to be mentioned that the reliability of the proposed generational dematerialisation indicator is expected to be the highest when analysing single countries, which results from the fact that the statistical data for different products are mostly available at national levels only.

The approach presented in this paper, as well as the analyses results, shows that the potential of the generational dematerialisation indicator is much higher than the potential of the commonly used methodologies. The conceptualisation of this indicator led us to new paths of strategic analyses in the process of creating sustainable management policy.

Moreover, the presented concept reveals the possibility for dematerialisation cross-analyses between and among different products (which is usually impossible on the international scale). Also, challenging for the future would be performing ex-ante calculations in intergenerational comparisons.

The generational dematerialisation indicator was shown to be a useful instrument for verifying the effectiveness of environmental and management policies in solving current problems in the field of product eco-effectiveness. Therefore, by implementing the presented approach, the management strategies can be created more effectively in the world, in single regions and on different levels. The modeling and simulation can be additionally extended internationally on the total natural capital.

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