The role of public sector policy in sustainable energy efficiency: an application of dynamic modelling

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ABSTRACT

Environmental protection and sustainability are long-standing issues in European Union policies. In this study, we focused on public policy related to waste management. Information on waste disposal guidelines is communicated to public authorities and citizens through public policy. The crucial question is whether the implementation of this policy achieves the objectives. The present analysis was based on a dynamic model of the repeated recycling and energy utilization process of sorted paper using a coloured Petri net. This model allowed for the isolation and monitoring of energy use in relation to the input amount, enabling the investigation of the potential energy efficiency of the paper recycling process. The breakpoint was calculated in terms of energy efficiency, gradual recycling and subsequent energy use. The calculation proved that, until this breakpoint is reached, recycling does not result in greater energy savings than the direct use of sorted paper for energy production. These findings have significant implications for the design and formulation of public policy for both the European Union and national governments.

KEYWORDS

public policy; energy efficiency; public sector; decision-making; waste management; Europe; dynamic modelling; breakpoint

INTRODUCTION

Human activity, intensifying through a focus on continued economic growth, is putting increasing pressure on the effective implementation of sustainability principles in relevant public policy (Dalby, 2019). The first clause of the EU's public energy policy emphasizes recycling and waste to improve sustainability. This measure has simultaneous benefits for both the economy and consumers (European Union, 2019). In addition to achieving a low-carbon economy, public energy policies aim to ensure that the energy consumed is safe, competitive, locally produced and sustainable, all of which are also enshrined in documents such as Agenda 21 and Agenda 2030. Thus, public policy has a direct link to sustainable development. The European Union (EU) package for secure, affordable and sustainable energy calls for a 40% reduction in greenhouse gas emissions by 2030 compared with 1990. The aim is to achieve leadership in renewables by 2030. As a result of the decrease in energy consumption, the EU expects to reduce its imports, reduce environmental pollution and preserve more domestic energy sources.

Material and energy management are of key importance in achieving these goals (Allen, 2008). To limit the risk of inefficient implementation of the public policy mentioned above, using an information tool that supports decision-making is appropriate. This tool will provide policy designers as well as those responsible for implementation with more detailed information on the behaviour of the processes for which they are responsible. The objective of this study is to propose an information tool for the public sector to manageenergy efficiency with particular reference to the waste management sector. The research question focuses on public policy where energy savings from recycling are considered unconditionally beneficial. Therefore, the research question sets out to test this by asking: Is recycling the best solution in terms of energy efficiency? The introductory sections put the analysis into a theoretical framework. The following sections describe the methods used – methods of case studies using dynamic modelling (Petri nets) followed by the specifics of the research framework using an overview of public policy and documents governing energy efficiency in the EU. The ‘paper recycling process’ defines a general flowchart of the researched material and energy flows, followed by sections containing a case study using a dynamic model and deriving a general function so that the breakpoint below which recycling becomes energy inefficient is found. The final section discusses the conclusions, limitations of the methods and examines other possible research directions.

IMPLEMENTATION OF PUBLIC POLICY

The quality of services provided by public institutions depends on the quality of information (Hub & Sedlák, 2014). The European Commission is the body that proposes new legislation, and the Parliament and the Council are the decision-making bodies. The member states then implement these policies, while the Commission ensures that the policies incorporated by the member states are adequately implemented (European Parliament, 2019). The political direction of EU member states is determined primarily by the focus of government policies with respect to European legislation. Relevant decisions with an actual environmental impact on energy sustainability processes are taken by national governments. The following discussion covers research papers that focus on the analysis ofmaterial and energy flows, supply chains or life cycle assessment (LCA) in the context of the public sector. Potts (2014) discusses inefficiencies resulting from public sector principles and points to the legitimate differences between efficiency in the private and public sectors. Aristovnik (2009) deals directly with measuring the efficiency of the public sector within EU countries. The author uses the evaluation of a system of selected indicators as a tool for measuring efficiency. Nutt (2005) addresses the extent to which decisions are influenced by the fact that the decision process occurs in the public sector. Öjehag-Pettersson (2019), using Sweden as an example, addresses the extent to which selected instruments can influence the results of public policy. It is evident that the problems resulting from inefficiencies inherent in public policies themselves and inefficiencies arising during their application can be eliminated to some extent by sufficient information support. In general, there are four reasons for so-called government failures: limited information, limited control of private-sector reactions, limited control over the bureaucracy, and limitations arising from the nature of the political process (Stiglitz, 1997; Peters & Pierre, 2014). Accurate and relevant information presented in a clear way can eliminate the problem of limited knowledge as the cause of government failure. Many authors have researched decision support processes and decision support systems in the public sector. As early as the late 1970s, Downey (1979) emphasized the need for public sector decision-making tools to offer different solutions. They should facilitate the processing and evaluation of information, and encourage human creativity. Downey mentions new perspectives on the concepts of optimization and algorithmization as additional suitable tools. In general, a decision support system is defined as an interactive system based on information technology (IT) that helps decision-makers use data and models to solve unstructured problems (Sprague, 1980). These tools can be divided into three groups: (1) generic, independent of the problem area in which a decision is to be taken; (2) specific to a concrete range of problems – systems are focused on information support in a particular area and provide information on the impact of various measures, or their combination in a specific area; and (3) specific to a concrete stage of decision-making, for example, systems supporting the identification of relevant players and factors for decision-making for particular problems (Boots & Lootsma, 2000). The following review papers discuss various decision-making methods and their applicability, providing a useful, comprehensive overview. For example, Button (1979) mentions the tools relevant for decision support in the public sector. In their work for NASA, Kerermic and Tukel (2006) demonstrate that modelling tools are commonly used to support public sector decision-making. They proposed an original mathematical model to support decision-making in the field of outsourcing, based on the comparison of selected indicators with elements of the set of values. Colin (1985) presented the use of models based on linear programming methods to support decision-making in the public sector. From the content and focus of these review papers, it was concluded that the application of scientific methods to decision support systems in the public sector can fill the gaps related to the potential inefficiency of decision-making. However, Boots and Lootsma (2000) point out that the concept of 'decision support' itself and all the methods connected with it are based on the premise that those who have faster access to better information will make better decisions. They mention that 30 years of experience with decision support systems in the public sector shows that the relationship between information and the quality of decisions is considerably complex. They draw attention to the need for public sector decision-making to meet at least three criteria: efficiency, effectiveness and legitimacy. Efficiency refers to the level to which the intended goal is achieved; effectiveness is the ratio of effort and effect attained; and legitimacy means that the decision is within the limits of the applicable legislation. However, they add that the legislation may limit the effectiveness of decision-making.

According to the classification presented by Boots and Lootsma (2000), the methods of modelling and analysis of material and energy flows belong to the group of tools intended for decision support in the public sector that focus on a specific range of issues. They meet the ideas generally defined by Downey (1979) and Sprague (1980). Methods based on material and energy flow require large volumes and high accuracy of input data. This also concerns the analyses of a limited section of the supply chain according to LCA, such as modelling processes in companies. The context of processes influenced by public policy is much broader, further increasing the need for accurate and sufficient data. To a certain extent, each similar model has the characteristics of a case study. The transferability of material and energy flows model on a general level is limited by the application of inductive methods (Ochrana, 2013). The application of the material and energy flows model is meaningful, especially in cases where the phenomenon researched can be described in its entirety, allowing for the results to be used in public sector decision-making processes. These methods are also covered by the problem presented by Boots and Lootsma (2000), who assume that those who have better information at the right time make better decisions. However, this assertion is not necessarily true under all circumstances, even though it constitutes one of the implicit preconditions for the workability of the method. However, the papers above demonstrate that, despite its limitations, the method is a source of reliable information in case-specific assignments.

Nevertheless, this decision-making support method is best applied where the problem to be decided has a multidisciplinary character and the process to be decided is measurable in physical units. As demonstrated by selected work over the last two decades, methods based on materiál and energy flows has been used to support public sector decision-making in the field of sustainability, which includes a number of public policies from waste to energy policy. Unless compliance with legislation is required, this tool can provide information about the direction of public policy and subsequently influence the legislation towards more effective achievement of objectives. Bagchi and Seung-Kuk (2001) used information on material and energy flows in their case study to optimize information systems in the South Korean port of Busan. The authors describe a combination of the public and private sectors, where supply chain analysis is used to optimize overall performance, and new findings are applied to the information systems used. Data for the models they used were obtained through a questionnaire survey. This combination is relatively specific and does not differ significantly from the application of similar methods in the private sector. Two years later, however, the use of material and energy flow models in the application of the LCA method for use in the public sector was more evident (Norris, 2003). A typical example of a study based on material and energy flow analysis for the public sector is the work of Amano and Ebihara (2005), who researched the effects of individual industries on selected types of emissions by performing analyses on material and energy flows. This study was conducted in selected regions of Japan. Among the suitable methods, the authors mention material flow analysis (MFA), LCA and partial economic equilibrium analysis. The problem of lack of input data, which is faced by most researchers using this method, is solved in the analysis of materiál flows, which includes working with the intensities of energy flows within the studied regions.

They use carbon dioxide (CO2) emissions as an indicator and then derive the consumption of materials from energy consumption. The data are sufficiently aggregated so they can be used to support decision-making in the public sector at the national and regional levels. The results can also be used to determine the direction of public policy in the field of sustainability. A study published only a year later was devoted to consideration of the usability of the oftendiscussed indicator, the ecological footprint. This indicator can be aggregated at the transnational level and can be used as a tool for policy decisions on sustainability (Collins & Flynn, 2006). Similar to the analysis presented by Amano and Ebihara (2005), the ecological footprint works with the estimated intensity of material and energy flows and presents the results in a comparable form. In the same year, another study dealt with information support for the public sector using analyses of material and energy flows in the field of organic waste treatment in order to minimize the volume of waste (Lang et al., 2006).

Allen (2008) describes the problem in an interesting way by emphasizing the importance of knowledge of material flows and their inventory for the needs of public sector decision-making. Allen states that materials are the basis of the economy, and their life cycles are the main determinant of environmental quality. The material flow data contained in the constructed accounts include the movement of materials from extraction to production, the use of products, and their reuse, recycling and eventual disposal. The accounts show emissions to the environment at each management step. Properly used material flow accounts can help improve public and private decision-making by influencing the use of materials and helping to avoid many types of waste (Allen, 2008). This statement implicitly includes the fact that ‘avoiding many types of waste’ also means ‘using available resources more sparingly’, which also applies to energy flows which, in practice, cannot be separated from material flows. Allen states that this materiál flow accounting can be a critical element of the 21st-century’s efforts to achieve the sustainability of natural resources. Eckelman and Chertow (2009) used MFA to investigate the potential for material recycling. The purpose of their study was to shape public policy on the island of Oahu, Hawai’i, aimed at limiting the import of raw materials to the island. Jasch (2009) discusses methods for investigating the negative effects of production on the environment, introducing the life cycle costing (LCC) method, LCA and MFA (Jasch, 2009). Essentially, these are variants of methods based on different perspectives of material and energy flows. Regarding the method of analysis of material and energy flows, Hendriks et al. (2010) state that previous research has already confirmed that its use in supporting environmental decision-making in administration is advantageous, especially at the regional level. Its advantages include a timely identification of priorities, the ability to analyse and improve the effectiveness of measures taken, and the ability to design effective strategies in the field of materials management. Other interesting papers in this field undoubtedly include Curry (2011) which presents research into the possibility of using a combination of MFA and ecological footprints to shape regional policy. Curry researches the entire region as one process, incorporating inputs and outputs. Both the ecological footprint and this approach are fully applicable to decisionmaking in the public sector because when the relevant material and energy flows are included, they provide a realistic picture of the consumption of raw materials and energy in the region. The disadvantage of these approaches is that it is not possible to separately monitor the individual supply chain sublinks; thus, it is difficult to find solutions to specific issues.

On the other hand, they make it possible to assess overall sustainability and, if necessary, allow comparison of the development of sustainability for individual regions, especially for ecological footprints. Papaspyropoulos et al. (2016) dealt with the analysis of sustainability in forestry by addressing the lack of input data for monitoring specific material flows using the method of material flow cost accounting (MFCA), deriving the volume of material flows from the identified financial flows. Johnson et al. (2017) researched the organizational structure and responsibilities within a supply chain characterized by material flows and customers. This study combines the issueof supply chain analysis in the form of material flows and the selection of suppliers of goods and services to the public sector. Jelse and Peerens (2018) discuss the specifics of LCA and environmental product declaration (EPD) methods for evaluating green procurement in the public sector. Like other authors, they agree that LCA, especially the processing of material surveys and energy flows, is data intensive and thus difficult for small and medium-sized enterprises (SMEs) to use due to costs. They state that a prerequisite for its use in the public sector is that LCA analyses should be processed by individual companies, so the public sector will have data available for its decision-making.

CASE STUDIES USING PETRI NETS METHODS

Case studies are included in qualitative research methods, focusing on real elements and interactions between them, based on a detailed study of one or a limited number of cases. The aim is to use the acquired knowledge to understand similar cases (Hendl, 2005; Stake, 1995). Yin (2009) speaks of a case study as a procedure for researching a predefined phenomenon that takes place in the present and has a real context. He divides case studies into exploratory analysis, descriptive case studies and test case studies. Exploratory analysis defines hypotheses or sets questions for further research to determine the acquired knowledge at a theoretical level, and to prepare materials for further research. Descriptive case studies provide the most comprehensive description of a phenomenon; in connection with the relevant theoretical basis, they seek an explanation of a specific phenomenon by analysing the causes. They attempt to discover new determinants, explore little-known ones and analyse them. Test case studies are similar to explanatory analyses, with the difference being that the goal is to verify the correctness of the theory. Material and energy flow management methods were applied for the purpose of information support in the public sector in the form of case studies, and dynamic modelling methods were applied. Coloured Petri nets were chosen as the tools for creating dynamic models. The general definition of a Petri net is that of Olej (1996). This definition makes it possible to mathematically write any type of Petri net. However, it needs to be modified for environmental modelling purposes. The revised definition follows; individual changes are then described under this definition:

Petri net is an bipartite directed graph defined as an ordered 5-tuple.

GPN = <P,T,QP,QT,QE>, where P is a finite set of places represented by circles, T is a finite set of transitions represented by lines or rectangles, where it applies to both sets: P ∩ T = 0

QP is an ordered 4-tuple QP = <C,IC,M0C,UP>, defining parameters k places of set P.

QT is an ordered 5-tuple QT = <QC,τ,PR,IF,UT>, defining parameters of r transitions of set T.

QE is an ordered 3-tuple QE = <IE,EE,LE>, defining parameters of arcs and is given by forward and backward incidence function.

An ordered 4-tuple, defining parameters k places of set P can be defined as a ordered 4-tuple QP = <C,IC,

M0C,UP>, where C is a finite set of colours used C, where IC: P × T → R × C, R where R is a set of real numbers, IC ((n,c)m,i,j), where m є <1,h>, i є <1,k>, j є <1,r> is a forward incidence function.

It is represented by m ordered 2-tuples <nm,cm>, where nm are elements of a set of real numbers, cm є C, for each arc from place pi є P to transition tj є T. On this arc can pass from place pi є P to transition tj є T nm є R tokens of colour cm є C.

M0C: P × R→C is a initial marking,M0C((n,c)m,i). It is for each place pi є P given by ordered 2-tuple <nm, cm>, which describes how many tokens in which colour occurs in places pi є P.

UP is an finite set of properties of tokens in places pi є P, UP = {up1, up2,..., upk}.

An ordered ř-tuple defining qualities r transitions of set T can be defined as: QT = <QC,IF,UT>

QC: T × P→R × C, where R is a finite set of real numbers, QC((n,c)m,i,j), where m є <1,h>, i є <1,k>, j є <1, r>, is a backward incidence function. It consist of m ordered 2-tuples

<nm,cm>, nm ϵ R, cm ϵ C, for each arc going from transition tj ϵ T to the place pi ϵ P. Though this arc can pass from transition tj ϵ T to the place pi ϵ P, nm ϵ R tokens of colour cm ϵ C.

IF > T × PR → {1,−1,0} is a incidence function und defines:

If IF(tj,prl) = 1 and the connection between transition tj ϵ T and predicate prl ϵ PR exist, is the transition enabled to fire tj ϵ T is fireable, if the value of predicate prl ϵ PR is TRUE.

If IF(tj,prl) = −1 and the connection between transition tj ϵ T and predicate prl ϵ PR exist, is the transition enabled to fire tj ϵ T is fireable, if the value of predicate prl ϵ PR is FALSE.

If IF(tj,prl) = 0 the connection between transition tj ϵ T and predicate prl ϵ PR, the firing of transition tj ϵ T is not influenced by predicate prl ϵ PR.

UT is a finite set of qualities of transitions tj ϵ T, UT = {ut1, ut2,..., utr}, which can be deterministic, stochastic or fuzzy.

A finite set of qualities of edges given by forward and backward incidence function can be defined as QE = <IE,EE,LE>

where IE is a finite set of inhibit arcs (ie), IE = {ie1, ie2,..., ieie}, EE is a finite set of empty arcs (ee), EE = {ee1, ee2,..., eeee} and LE is a finite set of logic (ordinary) arcs (le), LE = {le1, le2,..., lele}. (Olej, 1996)

This definition is unique in that it includes all possibilities and allows the mathematical writing of any type of Petri net. However, further expansion of the definition was necessary. Compared with the original definition presented by Olej, modifications had to be made, as the original definition works with full tokens, which is not suitable for models of material and energy flows where it is necessary to enter the parameters of these flows in decimal format.

ENERGY EFFICIENCY OF PAPER RECYCLING

The possibility of reducing overall energy consumption is also essential for EU public policy to reduce the environmental impacts in the form of greenhouse gas emissions. The proof that this is a current political issue is evidenced by the intensive work undertaken by EU institutions on this issue in recent years. On 26 June 2017, the Council of Europe issued the Directives on Energy Efficiency and Energy Performance of Buildings, which aimed to significantly reduce energy consumption by improving the energy performance of all types of buildings (European Council, 2019a). The revised Council of Europe Directive of 5 December 2018 states that achieving an energy efficiency of at least 32.5% is one of the critical goals to be met by 2030 (European Council, 2018). The conclusions of the European Council of 20 June 2019 emphasize the trend towards a circular economy and green and sustainable energy (European Council, 2019b). After the transformation of these goals into public policies, concrete steps to achieve them may consist of finding reserves in processes that no longer seem to offer significant savings potential or do not appear to be worth researching in terms of their energy characteristics. The US Energy Information Administration (EIA) states that paper and cellulose production ranks second after aluminium production in the United States (Skelton, 2017). Globally, the cellulose and paper industry ranks fourth among sectors in terms of energy consumption (Laurijssen, 2013). Therefore, it is possible to investigate some of the contexts of handling this raw materiál in more detail. These are some of the typical substances that have been recycled in many countries for a relatively long time (Otis, 2016). Analysis of the method and parameters of sorted paperhandling processes can provide support for the design and implementation of public policy aimed at paper recycling. Under certain conditions, it is better to burn paper rather than recycle it; thus, the issue of energy use in sorted papers is quite complex (Baťa & Kadlecová, 2011).

The aim of this case study is to analyse the process of sorted paper management implemented according to the principles of the general hierarchy of waste management, whose design is determined by public policy in terms of effect on energy savings. To evaluate the effective energy use of paper in the context of other influences, an overview should be provided of the energy flows of the part of the assessed system that is relevant from the point of view of such decision-making. It is also necessary to compare the total savings resulting from recycling and the possible energy gain from paper which can no longer be recycled and is used instead to generate energy. As the aim of the above-mentioned public policy is energy efficiency, it is energy that is the primary indicator in assessing the recycling process. The hypothesis was expressed as follows: when assessing the paper recycling process from the point of view of the obtained and saved energy, a breaking point occurs where recycling may be worse than incineration. This hypothesis also assumes that, under certain circumstances, automatic compliance with the recommendations set out in the European Waste Directive or in the Czech Waste Act (European Parliament and Council of the European Union, 2008; Ministry of the Interior of the Czech Republic (MVCR), 2019) may not always be in line with the objectives set out in the Council of Europe's documents to achieve desired energy efficiency by 2030 (Ministry of the Environment (MoE), 2019b; United Nations, 2015).

PAPER RECYCLING PROCESS

Following the waste management hierarchy, which is included in Directive (EU) 2018/851 of the European Parliament and the Council, a waste management method that corresponds to the highest possible item in this hierarchy (MVCR, 2019) should be selected. This is also in line with sustainability objectives, where waste management hierarchy grades waste according to the expected environmental burden. Thus, for sorted paper, recycling should be considered as a priority if possible, followed by subsequent energy recovery. The entire process is illustrated in Figure 1. In terms of energy efficiency, the recycling of paper can be demonstrated by energy savings (Baťa & Kadlecová, 2011). The overall energy savings compared with paper waste landfilling after the first use consists, first, of saving energy through recycling itself and, subsequently, from using paper waste for energy recovery. The question of whether it is right or wrong to burn sorted paper cannot be answered unequivocally. Paper-burning is one of the options that can contribute to increasing the overall energy efficiency of sorted paper processing. However, such research must also be complemented by an analysis of the positive effects associated with recycling. Determining the most energy-efficient and sustainable solution consisted of processing the model using a coloured Petri net, from which a general mathematically expressible relationship was derived between the proportion of sorted paper and the total energy effect from gradual recycling and subsequent incineration. The result was compared with the variant where the sorted paper would only be used for energy.

MODELLING OF ENERGY EFFECTS IN WASTEPAPER MANAGEMENT

The data used in this analysis of sorted paper were related specifically to the city of Děčín in the Czech Republic. The reason for this choice was that the available data cover a relatively long period. The defined issue can be researched in general, but specific data allowed the expression of specific conclusions and recommendations. The data were easily accessible on the city's website. Relating part of the calculations to a specific municipality aimed to evaluate the energy potential of using paper for heat production. It was expected that waste from this municipality will have a similar structure to other European cities. There was 22.1 kg of sorted paper per citizen of Děčín per year (1,116,000 kg of sorted paper per 50,500 inhabitants in 2011). The amount of sorted paper for the periods 2000–11 and 2013–18 is shown in Table 1.

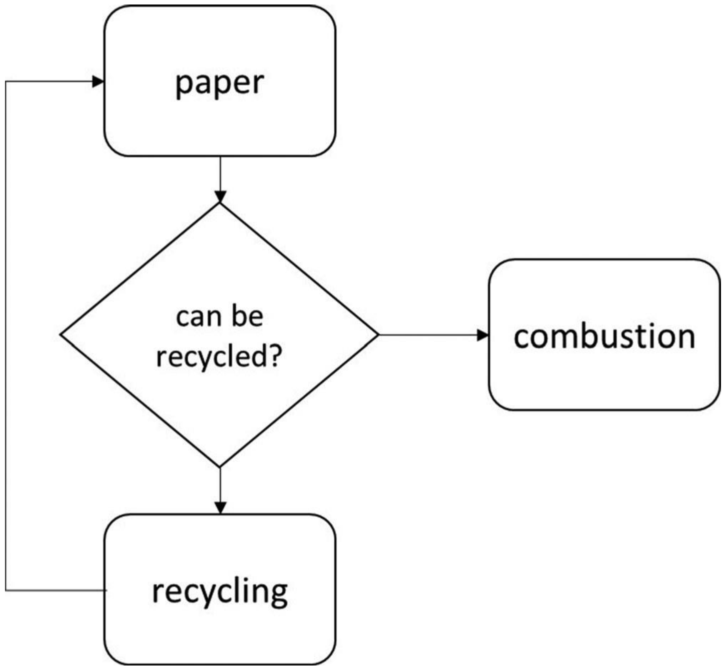


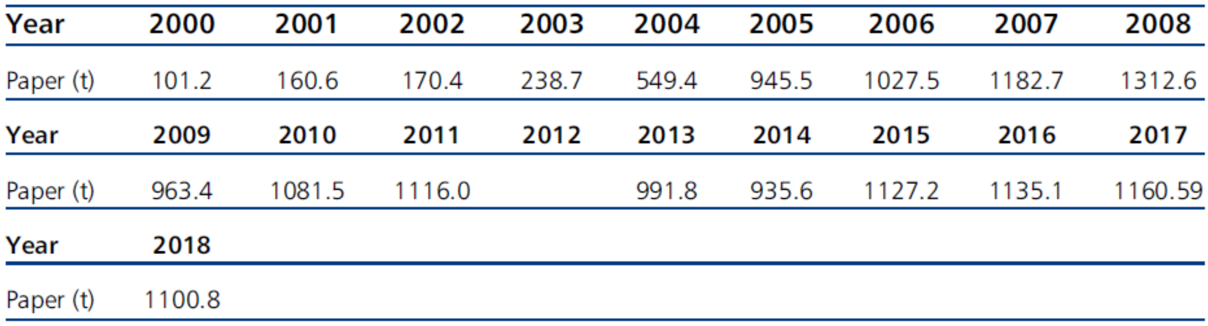
Figure 1. Flowchart of the sorted paper management process according to the waste management hierarchy.

Source: Authors according to MVCR (2019).

No data were found in 2012. However, it is clear from the above data that the total weight of sorted paper was approximately 1000 t/year. Specifically, the average for the period 2005–18 was 1074.45 t. Other data that needed to be taken into account in the model were the average percentage of sorted paper. The data that can be used for the overall proportion assessment of sorted paper were provided by the server named 'Unwrapped'. Unfortunately, this was only concerned with wrapping paper (Concept 42, 2019). From the data given in Table 2, it was calculated that in the period 2009–15, the percentage of sorted paper from packaging was 90%. Overall, the percentage proportion of sorted paper was probably less, according to the 'Waste Sorting' server, which calculated it at just below 80% (Concept 42, 2019). As of the date of this case study, no other data sources for the average proportion of sorted papers in the Czech Republic were found. However, the exact determination of these data was not necessary for the construction of the model because it can be specified at any time by entering new data. A value of 80% was used to enter the input variable into the basic model. Additional data that needed to be entered into the constructed model for the actual results were the amount of energy saved when the paper was recycled. The problem was that the data varied depending on the source selected. The US EIA determined the energy consumption, depending on the technology, at 1054.35–4219.2 MJ for 1 tonne (t) of recycled paper processed, while for the production of paper from wood, the production of 1 t accounts for 10,544.4–12,654 MJ of energy (Otis, 2016).

In contrast, the European recycling portal states that recycling 1 t of paper can save up to 14,400 MJ of energy, 26,000 dm3 of water and 3.5 m3 of landfill space (Bureau of International Recycling, 2019). According to Laurijssen (2013), in 2010, the consumption of primary energy to produce 1 t of paper in EU countries reached an average of 13,899.96 MJ. Interesting data are also available on the website of the city of Jihlava, which shows the results of similar measurements conducted in the Czech Republic. According to that, the production of 1 t of paper required approximately 240,000 dm3 of water and 16,920 MJ of energy. The production of 1 t of recycled paper used approximately 180,000 dm3 of water and 9900 MJ of energy (Jihlava, 2010). Based on the above data and given that there is a relatively high degree of uncertainty regarding the sub-parameters, it can only be stated with certainty that recycling saves energy. In accordance with the precautionary principle, the least favourable values were used. The energy consumption for the production of 1 t of paper was 16,920 MJ, and for the recycling of 1 t of paper it was 9900 MJ. If more accurate data are found, the model can be updated accordingly. It is now possible to proceed to the creation of the model. Given that in the period around 2009 there were several proposals prioritizing the energy use of paper over recycling (subsequently incorporated into Decree No. 482/2005 Coll.), it was possible to apply a combination of recycling and incineration. The basic module was a model of the process of energy recovery of sorted paper following the concept of the waste management hierarchy. Technically, paper can be

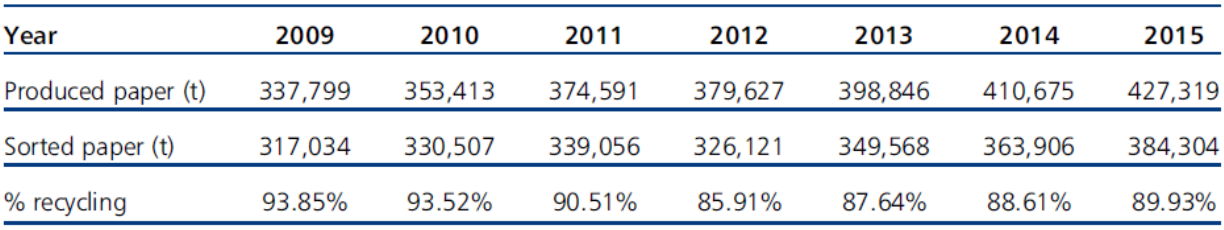
Table 1. Amount of sorted paper (tonnes) in the city of Děčín per year.



Year	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**
Paper (t)	101.2	160.6	170.4	238.7	549.4	945.5	1027.5	1182.7	1312.6
Year	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**
Paper (t)	963.4	1081.5	1116.0		991.8	935.6	1127.2	1135.1	1160.59
Year	**2018**								
Paper (t)	1100.8								

Source: Authors according to City of Děčín (2011, 2019).

Table 2. Production and share of sorted paper (tonnes) from packaging in the Czech Republic.



Year	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**
Produced paper (t)	337,799	353,413	374,591	379,627	398,846	410,675	427,319
Sorted paper (t)	317,034	330,507	339,056	326,121	349,568	363,906	384,304
% recycling	93.85%	93.52%	90.51%	85.91%	87.64%	88.61%	89.93%

Source: CZSO (2019b).

recycled several times. When the fibres are so damaged that further recycling is not possible, the paper can still be meaningfully used for energy. Figure 2 illustrates the modelled process. For the application of the model in a specific locality, the model calculation considered the entire volume of paper placed in the sorted paper containers in the city of Děčín. The paper volume that was finally destined for incineration (non-recyclable residue) was affected by the amount of paper out of the total volume that was removed from the waste stream. From the above data and the processing, it follows that this ratio was set at 80%/20%. Transport, economics, and other costs were ignored. In the period 2005–18, except 2012, an average of 1074.45 t.a−1 paper were placed in wastepaper containers in the city of Děčín. This paper could first be repeatedly recycled and then used as fuel for the production of electricity and heat. The model of its energy use was processed using a coloured Petri net and implemented in the Umberto 5.5 environment. This environment also supports decimal marking, which is an advantage. A specific feature of Umberto 5.5 software is that the environment works with an inanimate type of Petri net. At the same time, it allows the computation of the initial marking from any specified partial state.

For this reason, it does not make sense to analyse the properties of the net used. The model implemented using a coloured Petri net in the Umberto 5.5 environment is shown in Figure 3 and represents the flowchart process shown in Figure 1. The input at p6 was the paper for further processing. It was assumed that the input paper would be recycled six times and then recovered for energy in line with the data provided by the Bureau of International Recycling (2019). At each recycling step, 20% of the volume of sorted paper was lost (the total salvage efficiency was considered to be 80%). Transitions t7–t2 represent a repetitive recycling process applied to sorted and recyclable paper. Because the Umberto environment does not allow for modelling of the so-called living Petri net, it was not possible to model the

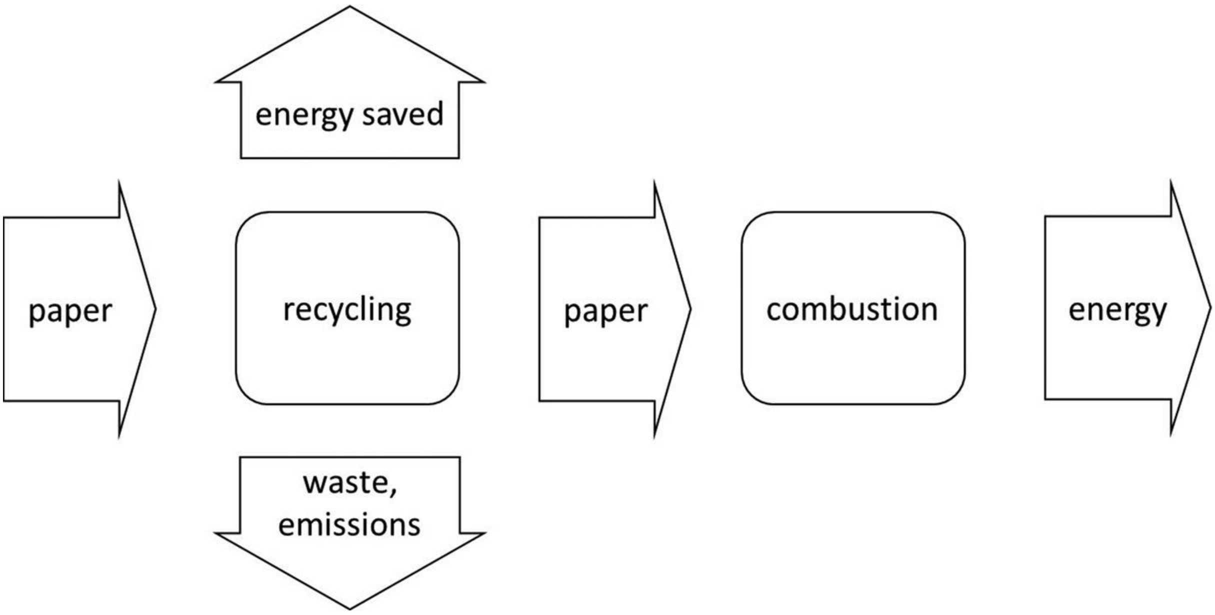


Figure 2. Modelled sorted paper handling process.

Source: Authors

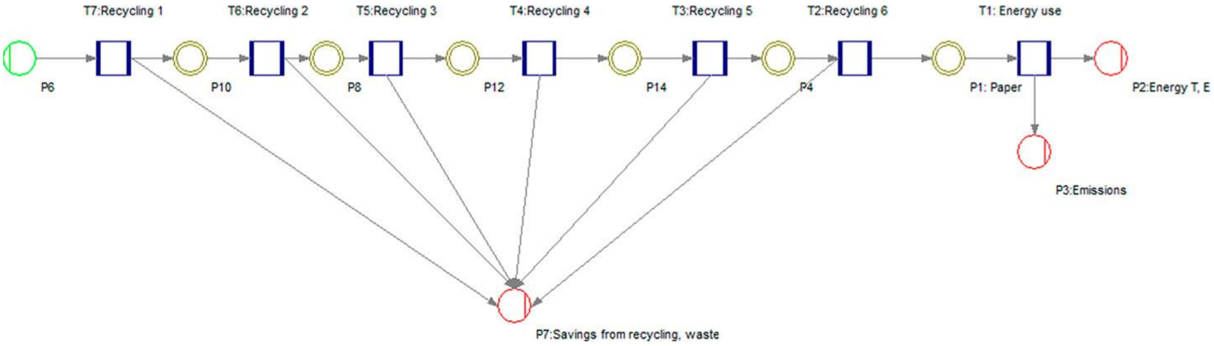


Figure 3. Model for information support in the case of paper recycling and energy recovery (heat production) implemented in the Umberto environment.

Source: Authors.

recycling process using a cycle in a single transition. This was, to some extent, an advantage, as the graphical representation of the model was better understood. The total energy saving effect from recycling is represented by p7, which also indicates the total paper loss in the process of subsequent recycling and salvage. Transition t1 represents the conversion process to thermal energy. The output is thermal energy (p2) and emissions (p3). The model (Tables 3 and 4) can be written mathematically as follows:

P = {p1, p2, p3, p4, p6, p8, p10, p12, p14}, T = {t1, t2, t3, t4, t5, t6, t7}, UP = {paper, thermal energy, CO, SO2, small particles, CO2, CH4, N2O, dust, unrecycled paper, energy saved}.

Because of the characteristics of the type of Petri net used, it was unnecessary to write the initial marking. The parameters of the paper energy utilization process were obtained by taking over some items from the wood-burning process and applying partial modifications of the parameters of this process. The items that differ from the wood-burning process were modified accordingly (Baťa & Kadlecová, 2011; Fritsche et al., 1989; 2001; IFU Hamburg, 2007; Novák, 2019).

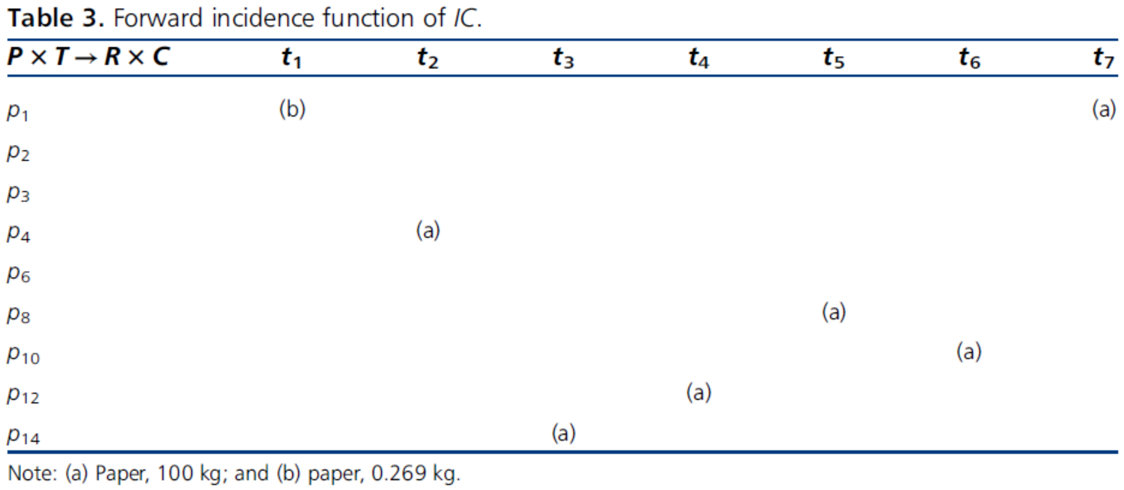


Table 3. Forward incidence function of *IC*.

$P \times T \rightarrow R \times C$	t_1	t_2	t_3	t_4	t_5	t_6	t_7
p_1	(b)						(a)
p_2							
p_3							
p_4		(a)					
p_6							
p_8					(a)		
p_{10}						(a)	
p_{12}				(a)			
p_{14}			(a)				

Note: (a) Paper, 100 kg; and (b) paper, 0.269 kg.

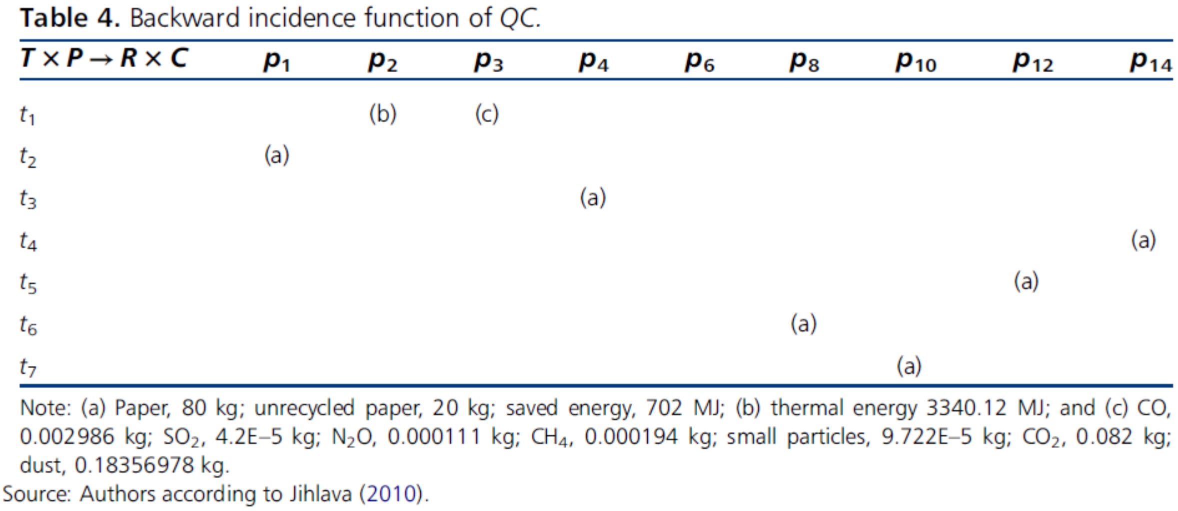


Table 4. Backward incidence function of *QC*.

$T \times P \rightarrow R \times C$	p_1	p_2	p_3	p_4	p_6	p_8	p_{10}	p_{12}	p_{14}
t_1		(b)	(c)						
t_2	(a)								
t_3				(a)					
t_4									(a)
t_5								(a)	
t_6						(a)			
t_7							(a)		

Note: (a) Paper, 80 kg; unrecycled paper, 20 kg; saved energy, 702 MJ; (b) thermal energy 3340.12 MJ; and (c) CO, 0.002986 kg; SO_2, 4.2E–5 kg; N_2O, 0.000111 kg; CH_4, 0.000194 kg; small particles, 9.722E–5 kg; CO_2, 0.082 kg; dust, 0.18356978 kg.

Source: Authors according to Jihlava (2010).

DETERMINATION OF THE BREAKPOINT

After entering the average volume of sorted paper for the city of Děčín into the model, it can be stated, based on the obtained results, that in the case of conversion to thermal energy only, 15,160.48 GJ of thermal energy would be generated from the 1074.45 t.a−1 paper. As the model assumed the paper would first be recycled six times, the amount of subsequently burnt residue corresponded to 3495.86 GJ of thermal energy. The amount of emissions generated is listed in Table 5.

An overview of the emissions produced provides essential information when deciding on waste management options and public policymaking, as this clearly defines the impact of incineration on the environment. Because of the different parameters of different devices, it is necessary to understand the results as indicative in case of uncertainty about the technical parameters of the device in which paper would be used for energy purposes. In the modelled case, these were the parameters of the energy utilization process of paper in a local 50 kW furnace without separators. It was also clear from the modelling results that there were significant losses in the paper recycling and collection process. In the modelled case, the estimated number of times the paper was recycled as input raw material was set to six in accordance with data from the Bureau of International Recycling (2019). If 80% of paper were sorted in each round, it was clear from the modelling results that out of the original 1074.45 t, a total of 792.457 t were lost in six consecutive collection and recycling cycles, which was 73.5% of the total input volume of paper. At the end of

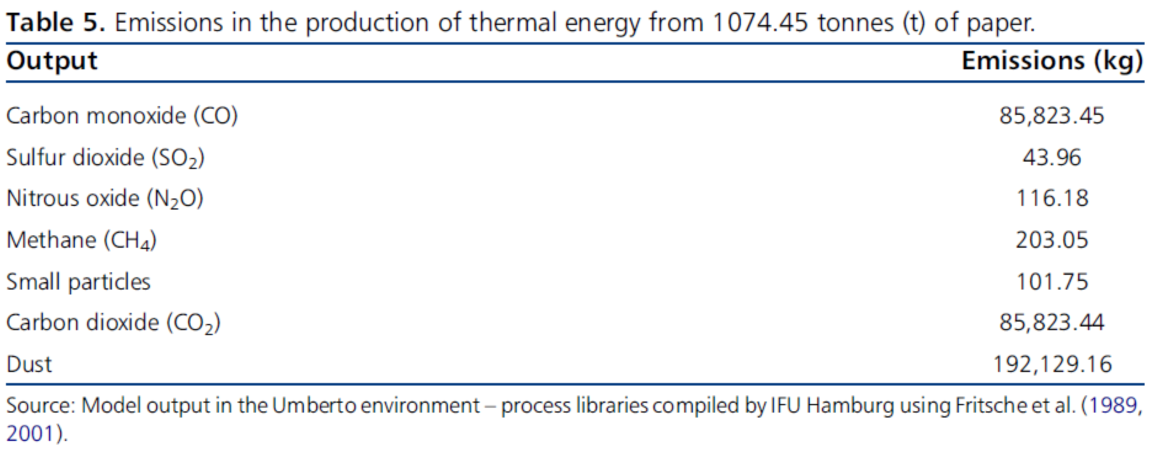


Table 5. Emissions in the production of thermal energy from 1074.45 tonnes (t) of paper.

Output	Emissions (kg)
Carbon monoxide (CO)	85,823.45
Sulfur dioxide (SO_2)	43.96
Nitrous oxide (N_2O)	116.18
Methane (CH_4)	203.05
Small particles	101.75
Carbon dioxide (CO_2)	85,823.44
Dust	192,129.16

Source: Model output in the Umberto environment – process libraries compiled by IFU Hamburg using Fritsche et al. (1989, 2001).

the recycling process, only 26.2% of the initially sorted paper was used for energy use. The total amount of energy savings from recycling represented the sum of savings from repeated recycling of the ever-decreasing volume of paper, and from the energy that could be obtained from sorted paper after the sixth round of recycling but that was no longer suitable for recycling. It was evident that the higher the percentage of paper that could be sorted and recycled, the greater the volume of energy saved and the greater the volume of raw materials obtained for energy use. Overall, the functional dependence between the percentage of sorted paper and the number of recycles can be expressed by the relation f (x):

$$y = x^n \quad (1)$$

where y represents the remaining percentage of paper from the original amount; x is the percentage of average sorted paper; and n is number of recycling rounds. The relationship can be expressed graphically, as shown in Figure 4, which shows how the total residual volume of recyclable and subsequently energy-efficient paper decreases with an increasing number of recycling rounds. Based on the model results, it was possible to compare the extent to which recycling (according to the requirements of the waste hierarchy; MVCR, 2019) was more efficient in terms of energy savings than energy recovery itself. As can be seen from the modelled process, with each subsequent step the savings from recycling decrease as the amount of material to be recycled decreased. This effect is not noticeable in real conditions because there is no clear, direct relation to the original volume of the sorted amount of paper. As can be seen Figure 4, after six rounds of recycling, only a quarter of the original amount remains from the original volume for energy recovery. For the city ofDěčín, the energy efficiency of this procedure, given by the sum of savings from all recycling steps and the subsequent energy gain from non-recyclable paper, was 27,815.26 GJ in the form of energy savings and 3495.86 GJ in the form of thermal energy for the amount of paper entered into the model. Therefore, there was an overall effect on saving and gaining energy of 27,815.26 + 3495.86 = 31,311.12 GJ. In contrast, if the paper had not been recycled and the entire volume of sorted paper was immediately used for energy, 13,335.65 GJ of energy would have been obtained. To construct and verify the correctness of the following formula, the results were also obtained from the model in terms of 1 t of paper. Incineration of 1 t of paper produced

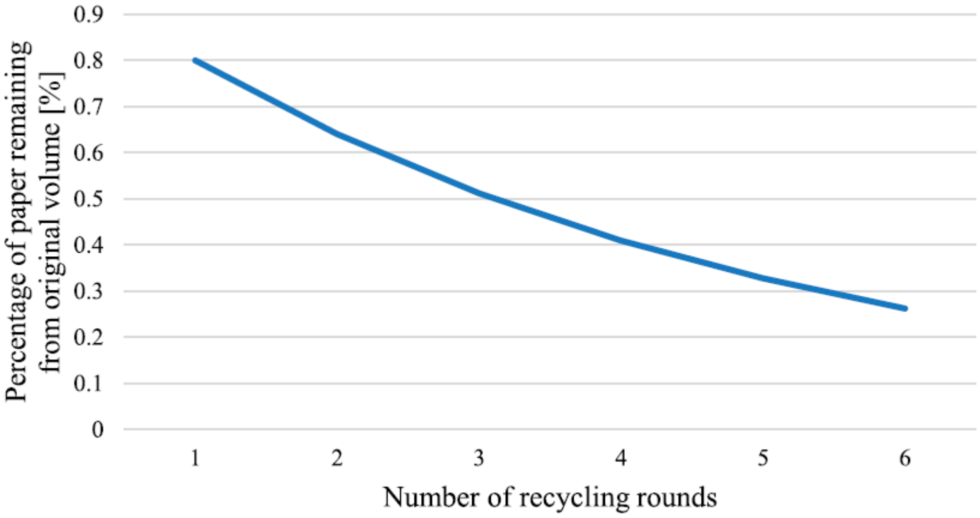


Figure 4. Influence of the number of recycling rounds on the proportion of paper remaining from the original amount.
Source: Authors according to Božek et al. (2003) and Concept 42 (2019).

12.41 GJ of energy. One round of recycling 1 t of paper saved 7.02 GJ. Six rounds of recycling and subsequent burning of 1 t of paper would result in a total saving of 25.89 GJ due to recycling and gaining of 3.25 GJ of energy by the comprehensive use of the non-recyclable residue with 80% sorting efficiency, which makes up 29.14 GJ. In this case, it was evident that it was better to recycle paper first and then use it for energy recovery. However, it was also clear that, because the energy benefit from recycling was less than the energy obtained by combustion of energy appreciation of the same weight of paper, there is a specific rate of paper sorting, which will be a breakpoint when it will be more energy-efficient not to recycle paper but to use it immediately for energy production. The total savings calculated by the model apply to six rounds of recycling as illustrated by the following equation:

$$S = er + a \times er + a^2 \times er + a^3 \times er + a^4 \times er + a^5 \times er + a^6 \times eh \quad (2)$$

where S is the amount of energy saved from recycling; a is the percentage of sorted paper; er is the value of energy savings due to recycling of 1 t (e.g., paper compared with the production of paper from wood); eh is the amount of energy that can be obtained by burning 1 t of material, forexample, paper; and n is the number of recycling rounds. After modification and generalization:

$$S = a \times e_r \frac{1 - a^n}{1 - a} + a^{n+1} \times e_b \tag{3}$$

The break point for this process is therefore given by the equation, which is obtained by substituting

the values for energy savings from recycling and energy gain from burning 1 t of paper into

equation (3):

$$7.02 + a \times 7.02 \frac{1 - a^5}{1 - a} + a^6 \times 12.41 = 12.41 \tag{4}$$

This equation cannot be solved analytically, but a numerical solution can be found, for example, by using MS Excel. According to the calculation in the MS Excel environment, this value was equal to 43.433%. This leads to an essential conclusion for public policymakers and implementers in the field of waste management. Unless at least 43.433% of the sorted paper is achieved in waste collection and sorting systems, better results in terms of overall energy efficiency will be achieved by burning paper directly rather than recycling it. The total value of the energy gain then remains constant at the level of 12.41 MJ.t−1, regardless of the degree of sorting. The overall energy balance of the system begins to improve only when this level of sorting is reached. This value represents the breakpoint when, from the point of view of energy balance, recycling begins to make sense. The relationship between the proportion of recycled paper and the total recycling effect, which was constructed based on equation (4), is shown in Figure 5. Figure 5 shows the overall development of energy savings using the sorted paper. The recycling + combustion curve represents the general process of energy gains in recycling and subsequent energy use. The combustion curve shows the total energy gain if the paper was not recycled but burned immediately. The graph verifies the assumption that recycling may not always be a suitable solution but that it is still necessary to consider it within the context of the overall waste collection and sorting system. Due its exponential curve, it is clear that each additional percentage of sorted waste is significant if the system moves towards the top right corner of the graph (i.e., the percentage of sorted paper is high). For 80% of sorted paper, the total energy benefit was 29.15 MJ.t−1, from 1 t. If the proportion of sorted paper shifted to 85%, the total saving would be 33.82 MJ.t−1, and for 99% of the sorted wastepaper it would be as high as 52.76 MJ.t−1. Another possible determinant could be the transport of paper for recycling, which

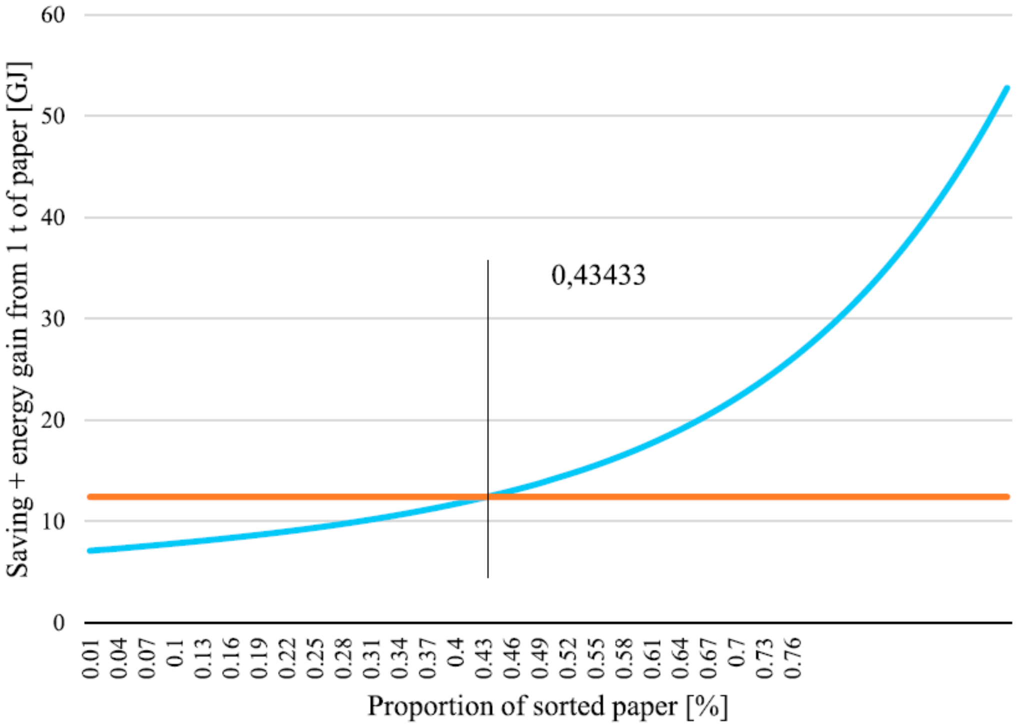


Figure 5. Comparison of energy gains from the use of paper in recycling and subsequent incineration without recycling.
Source: Authors.

would move this system to lower values. However, as the transport analysis was quite complex, it was not included.

DISCUSSION AND CONCLUSIONS

The results of the modelling confirmed the assumption expressed in the hypothesis and provided an answer to the research question. Recycling is not always the best solution in terms of energy efficiency. The existence of breakpoints has been proven, below which, in the case of a decrease in the proportion of sorted wastepaper, it is more energy efficient not to continue recycling sorted paper. Thus, a potential source of energy inefficiency in recycling processes was identified, which is not easily detectable when analysing readily available statistical data. Therefore, it was proved that a conflict exists between the content of EU public policy that regulates the waste hierarchy and the actual experience of managing the waste recycling process for energy savings and a low carbon economy. Nevertheless, the governments of the individual territories of the EU use this public policy to create their own regulatory frameworks. These are subsequently transformed into legal norms in the form of a requirement to achieve energy savings and to apply the concept of the waste management hierarchy. An example is Act 185/ 2001 Coll. on waste and on the amendment of other laws (MVCR, 2019). To construct the model, it was necessary to obtain information about the collection, recycling process, and incineration of paper. Due to variability, the least favourable variant was selected for the evaluation. If real values for energy savings from recycling in particular were more favourable, the set breakpoint would be shifted to lower values, which would mean that recycling would be more effective even with a lower percentage of sorted paper than originally set. Although it can be generalized, the limitations of the presented tool lie in consideration of the following points: (1) similar results can be obtained for the processing of those types of sorted waste for which only a limited number of recycling rounds is possible; (2) after recycling, it must be possible to use the considered waste for energy recovery; and (3) the recycling process of given waste must be associated with energy savings. This view can also be applied to waste produced from renewable sources. In the case of a certain type of non-renewable resource (e.g., plastics), this approach is questionable. A necessary condition for its applicability is that the monitored waste must have a limited number of possible recycling rounds, and it must be possible to also use it for energy recovery. Therefore, the proposed model represents a tool that can be used, especially within the EU, for estimating the conditions in the sorted paper handling component of the waste management process. The model also enables monitoring of the amount of paper remaining from the original amount at the specified, expected percentage of sorting for energy use. It is also possible to monitor the total volume of paper loss from the original input amount due to losses incurred in the process of collecting sorted waste. The model also includes the process of burning paper, including associated emissions. In addition to information on the amount of energy that can be obtained through sorting and recycling, it thus provides information which can be useful for shaping local and regional policy in particular, as well as information on the possible burden on the environment. The process of obtaining energy also accounts for losses during conversion.

At the same time, the parameters can be easily adjusted to the choice of the software used; thus, the results of the model can be refined for specific conditions. At the national level, the results predicted by the model can be helpful, especially in setting policy in the field of sorted paper management. Owing to the modelling tool used, one input or output parameter can be entered, and the model calculates all other values, working in both directions. Therefore, it is possible to research not only how much energy is generated or saved from the specified volume of paper, but also how much paper is needed to obtain the specified amount of energy or, for instance, how much paper can be processed before the specified volume of air pollutants is reached. The universal applicability of the proposed model appears to be particularly useful in covering the diverse information needs of governments in meeting public policy objectives aimed at achieving higher energy efficiency of such processes.Based on the analysis of the data from the modelled process, the model was supplemented by verification of the possible existence and the subsequent determination of the breakpoint, which was required for the minimum percentage proportion of sorted paper when it still makes sense to recycle paper for energy gain. This brings a new perspective on the effects of recycling, demonstrating that even with a relatively large percentage of sorted paper (< 43.4%), recycling can be a less effective option in terms of overall energy balance and can thus lead to overall lower energy efficiency in waste recycling processes. In general, the results obtained in this case study present an original method for evaluating the effects of recycling. The analysis of energy flows in the combined paper recycling and incineration process establish the existence of a breaking point for a specific percentage of waste sorting. The determination of a breakpoint in relation to the percentage of sorted waste expands the theoretical foundations for assessing waste management processes, while also bringing practical results. It was concluded that, assuming an average of 80% of paper waste is sorted, only 26.2% of the original amount remains after six rounds of sorting and recycling. Furthermore, the amount of energy and emissions that will be generated or saved by a gradual recycling process and the subsequent energy use of the specified amount of sorted paper has been determined. The breakpoint was set as the minimum percentage of sorted waste when recycling still makes sense in terms of energy savings. These outputs represent a further step in setting up public policies in the EU so that energy efficiency objectives can be more effectively achieved through implementation at national, regional, and local levels. The developed model, through analyses of material and energy flows, demonstrates an additional method of providing crucial information on the nature of processes to feed into public policy in the field of sustainable energy. Mere knowledge of the existence of possible turning points in waste sorting can be used to supplement EU legislation.

Consequently, it can be concluded that this is a specific tool to support governments in the development of public policies and their implementation. In comparing our conclusions with the results of other authors, there are other sources that deal with some aspects researched in our study. For example, Laurijssen et al. (2010) also reached the conclusion that recycling is beneficial in terms of energy balance, which is also our assertion. However, we went further by including the conditions under which this is most likely to occur. Other research deals with production processes, recycling, or paper combustion as separate entities (e.g., Cabalova et al., 2011; Torretta et al., 2014) while our study considers all of the above processes. This study is based on the conditions defined in the section headed ‘Modeling of energy effects in wastepaper management’. However, the fact that an exact determination of the breakpoint can differ depending on the environment needs to be taken into account. Ferrara and De Feo (2021) proved the influence of a specific production method for both paper and energy on the energy parameters of the process, which would lead to a potential shift of the breakpoint in different environments. The parameters of the tool we designed can easily be adjusted to specific conditions in the case of a dynamic model and derived functions. The confirmation of the hypothesis opens up other areas of research, for example, proving the existence of breakpoints for other parameters of the researched process and a change of result if the systém boundaries are defined in a broader manner and include other connected processes. In conclusion, it can be stated that the results of the modelling confirmed the assumption expressed in the hypothesis that when assessing the paper recycling process from the point of view of the obtained and saved energy, a breaking point occurs where the recycling process may be a worse option than incineration, which has serious implications for public policy (European Parliament and Council of the European Union, 2008; MVCR, 2019) if the Council of Europe hopes to achieve energy efficiency by 2030 (MoE, 2019b; United Nations, 2015). Therefore, the importance of correctly defining public policy cannot be underestimated.

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