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BIORESOURCE TRANSITION TOWARDS SUSTAINABLE BIOECONOMY

Summary of the Doctoral Thesis

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To be granted the scientific degree of Doctor of Science, the present Doctoral Thesis has been submitted for the defence at the open meeting of RTU Promotion Council on August 24, 2020 at the Faculty of Electrical and Environmental Engineering of Riga Technical University, 12/1 Azenes Street, Room 115.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for the review to Riga Technical University for the promotion to the scientific degree of Doctoral of Science is my own. I confirm that this Doctoral Thesis had not been submitted to any other university for the promotion to a scientific degree.

Lauma Žihare ………………………………….. (signature)

Date: …………………………………..

The Doctoral Thesis has been written in English. It consists of Introduction, 3 chapters; Conclusions; 71 figures; 18 tables; 25 mathematical formulas; the total number of pages is 145. The Bibliography contains 271 titles.

CONTENTS

ABBREVIATIONS

EU – European Union
EC – European Commission
UK – United Kingdom
JRC – Joint Research Centre
IAP – invasive alien plants
IAS – invasive alien species
NPV – net present value
MCDA – multi criteria decision analysis
AHP – analytical hierarchy process
TOPSIS – the technique for order of preference by similarity to ideal solution
DMC – domestic material consumption
DMI – direct material input
IRR – internal rate of return
OECD – Organisation for Economic Co-operation and Development
R&D – research and development
R&I – research and innovations
RD&D – research, development and demonstration
GDP – gross domestic product
GE – general electric
SDG – sustainable development goal
TRL – technological readiness level
CO_2 – carbon dioxide
SO_2 – sulphur dioxide
NO_x – nitrogen oxide
ISO – International Organisation for Standardisation
X_{ij} – normalized value (AHP)
A_{ij} – pairwise matrix elements (alternatives)
W_{ij} – priority vector
n – number of alternatives
n_{ij} – normalized value (TOPSIS)
v_{ij} – weighted normalized value
d_i^+ – distance to ideal solution
d_i^- – distance to negative solution
$I_{N,ji}^{\pm}$ – the normalised value of individual indicator i
M_{ad} – moisture content of the test portion used for determination of ash content (after ISO 18122), wt. %
Q_a^d – gross calorific value at constant volume, J/g
m – mass of sample, g
$Q_{N,S}$ – correction of heat, considering formation of nitric acid, J
Q_S – correction of heat, considering formation of sulphuric acid, J
H_0 – gross calorific value of the analysed fuel, J/g
S^d – sulphur content in the analysed sample (on dry basis), %
$Q_{V,gr,d}$ – gross calorific value of dry mass at constant volume, J/g
M_{ad} – moisture content of general analysis sample (after ISO 18125), wt. %
$Q_{p,net,d}$ – net calorific value of dry mass at constant pressure, J/g
H^d – hydrogen content in the analysed sample (on dry basis), wt. %
O^d – oxygen content in the analysed sample (on dry basis), wt. %
N^d – nitrogen content in the analysed sample (on dry basis), wt. %
$q_{p,net,ar}$ – net calorific value for sample as received at constant pressure, J/g
M_{ar} – total moisture content, wt. %
P – patent indicator: applications to the European Patent Office per million inhabitants
c – gross domestic expenditure on R&D by sector
NMMO – N-methylmorpholine-N-oxide
CAGR – compound annual growth rate
CIS – Commonwealth of Independent States
DAISIE – Delivering Alien Invasive Species Inventories for Europe

$I_{S,j}$ – weighted sub-indicator, in dimension j
W – weight of variable i in dimension j
I_{CSI} – complex index of alternative I
M_a – market attractiveness total score
Z – estimated rating score
k – coefficient
f – number of factors
B_{max} – max rating score
R – relative indicator of product competitive advantages
B – new product score estimation
B_{comp} – strongest competitor score estimation
m_1 – mass of the empty dish plus lid, g
m_2 – mass of the dish, lid and test portion before drying, g
m_3 – mass of the dish, lid and test portion after drying, g
NOBANIS – The European Network on Invasive Alien Species
GISD – Global invasive species database
MedPAN – network of Marine Protected Areas in the Mediterranean
EASIN – European Alien Species Information Network
Sc – *Solidago Canadensis*
Hs – *Heracleum Sosnowkyi*
PPW – potato peel waste
CG – coffee grounds
A_d – ash content, wt. %

INTRODUCTION

Topicality of the Doctoral Thesis

After rapid fossil economic development an estimation of resource insufficiency is evident. After global economic crisis in 2008, responsive actions by national governments rise, tightening credit markets lead to subsequent increase in borrowing costs that reduces the amount of capital available for investing in biotechnology research and development, that could lead to high-risk start-up firms and cause another global economic crisis. Therefore, it has become a push towards bioeconomy and necessity for research and infrastructure for alternative energy and sustainable agriculture. Combining resource depletion with climate change mitigation aims bioeconomy share an exponential growth towards more sustainable economy all over the world. A global trend that bases on biological resource use is in the centre of scientific researchers', policy makers', different stakeholders' and society behaviour. However, bioeconomy cannot substitute fossil resources with bioresources to the same extent to ensure the consumption of existing demand. Initial aims towards sustainable European bioeconomy were largely diverted towards bioenergy direction. Updated European bioeconomy strategy emphasizes not only bioenergy, but also creation of products with higher added value.

There are several limitations for bioresource production, therefore a methodology for smart bioresource selection, production and processing should be initialized within different levels of development.

The transition to sustainable bioeconomy with a holistic approach on a global level would benefit national bioeconomy development, climate change mitigation and innovation transfer.

There is still no common international method for determining, measuring, and comparing the extent of bioeconomy sustainability.

Composite indexes have been applied for evaluation of various complex phenomena, e.g. sustainable development, company sustainability [1], biorefinery complexity [2], and rural sustainable development [3], [4]. One of such indicators related to environmental dimension is the eco-innovation index that is used to describe the eco-innovation progress in EU member countries. Eco-innovation index is composed of 16 indicators that are grouped into five major groups: eco-innovation inputs, eco-innovation activities, eco-innovation outputs, resource efficiency, and socio-economic outcomes. Eco-innovation progress is described by the eco-innovation scoreboard [5]. However, there are no studies exclusively regarding composite index for bioeconomy. Like the concept of sustainability, a sustainable bioeconomy must be assessed at several levels: resources, products, companies, industries, national and global based on main pillars of sustainability (environmental, social, and economic).

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The Aim and Tasks of the Doctoral Thesis

The aim of the Doctoral Thesis is to develop an integrative methodology for the assessment towards sustainable bioeconomy through bioresource transition assessments using top-down and bottom-up approaches, transdisciplinarity analysis, and underused biomass potential use. The main contribution of the Thesis ascends from an integrated multi-level approach, that considers technical, socio-economic, environmental and market aspects. Output of the Thesis consists of: the assessment of bioeconomy factor interlinkages that could be further used for composite sustainability index creation and development of bioeconomy effectiveness index that helps to determine how effectively the bioeconomy is developing at a national level; several underused biomass potential use cases for Latvia; technology and product innovation commercialization framework and transdisciplinary market and economic assessment for cases done with collaboration with different stakeholders; experimental analysis for specific case of invasive species application. A case of triple factor nexus is also presented: policy, research and innovations, and technology nexus for European Union countries. As a result, the empirical model presents the mathematical description of policy, research and innovation, and technology link benchmark.

In order to reach the aims of the Thesis, the fallowing tasks were set:

1) to assess bioeconomy understanding and create consolidated view on bioeconomy;
2) to assess disciplinarity approaches towards sustainable bioeconomy;
3) to identify bioeconomy affecting factors, their interlinkages and propose possible nexus assessments;
4) to identify factor characteristic indicators;
5) to create factor nexus benchmark;
6) to create methodology for bioeconomy efficiency measures;
7) to identify potential bioresources that are underused and asses their potential value towards effective resource transition proposing new or existing bioresource value chains and their priorities;
8) to provide innovation transfer with market and economic analysis framework to determine if innovative bio-based product or technology would have the potential of entering market successfully;
9) to validate bio-resource potential with experimental analysis.

Research Methodology

The research methodology is based on three interconnected parts according to the proposed multi-level approach for assessing bioresource transition to sustainable bioeconomy development, through innovation and a transdisciplinary approach. The research methodology is divided into three main levels that permeate this transition – macro-level, which determines the global trend in economic development (the emphasis in this work is on the European level); meso-level, which is the institutional level; and micro-level, which determines a specific niche, in this case specific bioresources and their potential. Several methods, factor analysis, indicator analysis, benchmarking, triple-helix, and multi-criteria analysis methods have been used in this work.

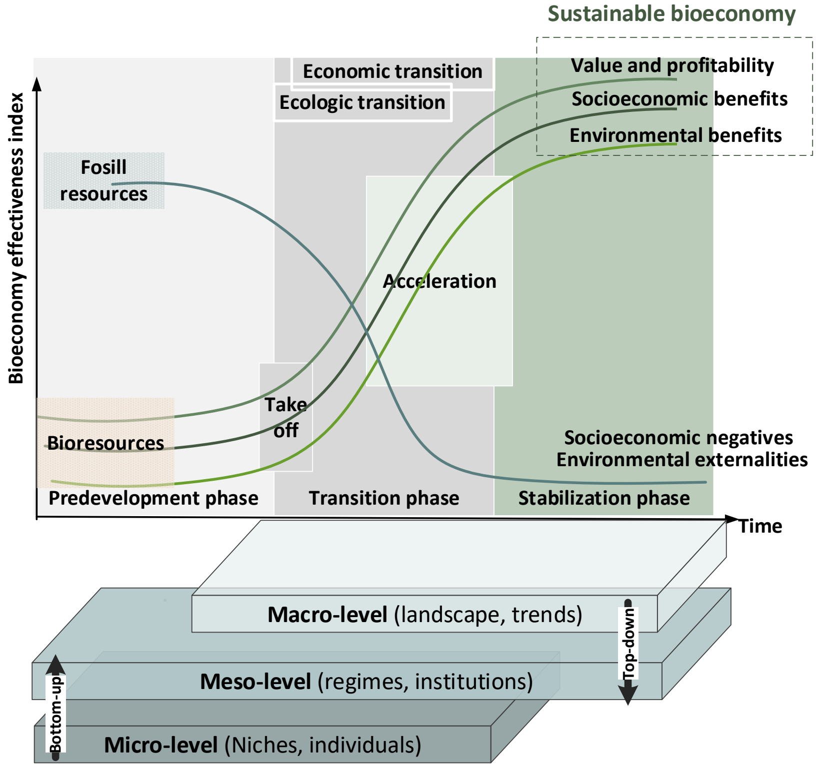

Fig. 1. Generic description of the bioresource transition.

The aim and the process are shown in Figure 1, where the main emphasis is on bioresource use promotion towards sustainable bioeconomy, that results in value and profitability, socioeconomic benefits and environmental benefits. The assessment that helps this transition and understanding of situation goes through three levels:

- Macro-level (top-down approach) is focused on bioeconomy development assessment based on factor analysis, case of European Union triple factor nexus through indicator approach is applied as case study to determine benchmark. A composite indicator for bioeconomy effectiveness for international comparison is created.
- Meso-level focuses on transition phase through innovation transfer framework, market and economic analysis, and transdisciplinary approach, taking into account different stakeholder requirements and opinion.
- Micro-level (bottom-up approach) focuses on estimation of potential value of different underused bioresources and management system. This part applies decision analysis and experimental analysis.

Scientific Significance

The Thesis is of high scientific significance in the Latvian and international contexts due to the fact that the investigation and analysis of bioresource transition is a topical research area of bioeconomy development. Three innovative methods have been developed and approbated within this Thesis. The first method is intended for bioeconomy efficiency measurement, the second can be used for innovation transition assessment and the third – for bioresource value assessment. This Thesis can be used as guidelines for further scientific studies towards bioeconomy development and bioresource assessments for bioresource value evaluation with holistic analysis approach.

Practical Significance

The Thesis is of high practical significance in the Latvian and European context. The research results provide a novel multi-level approach, which can provide a significant contribution a) for several bioeconomy stakeholders at national, sectoral, and international level; b) for policy makers in more effective bioeconomy development path determination; c) at a regional level for municipalities with invasive species new management plan and bioresource value notion; d) for entrepreneurs and different stakeholders; e) for society in effective use of resources; f) for scientific and research community in the agricultural and forestry fields who carry out research on related topics and can employ the scientific findings from this project in their further research.

Approbation of the Research

The results of the Doctoral Thesis have been presented at 6 conferences and in 18 scientific publications and 2 monographs.

The research results have been discussed and presented at the following **conferences**.

1. International scientific conference "EUBCE 2020 28th European Biomass Conference & Exhibition", with paper "Country level sustainability evaluation of bioeconomy" 2020, Marseille, France
2. International scientific conference "Biosystems Engineering 2019", paper "A holistic vision of bioeconomy: the concept of transdisciplinarity nexus towards sustainable development" 2019, Tartu, Estonia.
3. International scientific conference "Conference of Environmental and Climate technologies 2019", papers "New vision on invasive alien plant management system", "Obtaining the factors affecting bioeconomy", "Case Study of Aizkraukle Region in Latvia", and "Priorities determination of using bioresources. Case study of *Heracleum sosnowskyi*" 2019, Riga, Latvia.
4. International scientific conference "Conference of Environmental and Climate technologies 2018", papers "Multi criteria analysis for products derived from agro-industrial by-products", "Analytical framework for commercialization of the innovation: case of thermal packaging material" 2018, Riga, Latvia.
5. International scientific conference "Biosystems Engineering 2018", papers "The potential use of invasive plant species as solid biofuel by using binders", "Evaluation of reed biomass use for manufacturing products, taking into account environmental protection requirements" 2018, Tartu, Estonia.

6. International scientific conference "Conference of Environmental and Climate technologies 2017", papers "Bioeconomy mapping indicators and methodology. Case study about forest sector in Latvia", "Market opportunities for cellulose products from combined renewable resources", "Single cell protein production from waste biomass: comparison of various agricultural by-products", "Invasive Species Application in Bioeconomy. Case Study *Heracleum sosnowskyi* Manden in Latvia", "Carbon storage in wood products", "Methodology for estimation of carbon dioxide storage in bioproducts" 2017, Riga, Latvia.

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1. **Zihare, L.,** Kubule A., Dolge K., Muizniece I., Blumberga D., "Country level sustainability evaluation of bioeconomy, 2020, EUBCE proceedings (submitted).
2. **Zihare, L.,** Kubule, A., Vamza, I., Muizniece, I., Blumberga, D. Bioeconomy triple factor nexus through indicator analysis. *New biotechnology*, 2020 (submitted).
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Monographs

1. Scientific monograph "Sustainable Energy Sources", Barisa, A., Blumberga, A., Grāvelsiņš, A., Rochas, C., Blumberga, D., Dace, E., Vigants, E., Romagnoli, F., Galindoms, G., Vigants, Ģ., Veidenbergs, I., Ziemele, J., Rošā, M., Sarmiņš, R., Kalniņš, S., Prodaņuks, T., Kirsanovs, V. Editor **Lauma Zihare**, RTU Press, 2018, 146 p. ISBN 978-9934-22-017-3.
2. Scientific monograph "Development of Energy Planning in the Local Municipalities of Latvia", Kamenders, A., Barisa, A., Blumberga, A., Rochas, C., Blumberga, D., Pakere, I., Dzene, I., Burmistre, I., Muižniece, I., Veidenbergs, I., Ziemele, J., Kļavenieks, K., Kašs, K., **Žihare, L**., Sniega, L., Žogla, L., Rošā, M., Kalniņš, S. Riga: RTU Press, 2020, 172 p. ISBN 978-9934-22-062-3.

1. METHODOLOGY

Sustainability has become a global trend that is theoretically sought by all sectors and countries. Another widespread tendency in recent years is the shift towards the use of knowledge-based bio-resources within the economy for the production of higher value-added products, and the subsequent development of the bioeconomy with sustainability objectives in mind [2].

Methodology consists of three level analysis (Fig. 1.1): macro-level analysis method, using top-down approach bioeconomy assessment on international scale has been implemented; meso-level assessment, where transdisciplinary approach is applied as various stakeholder interests are taken into account; and micro-level assessment, where particular underused bioresource potential has been assessed and new invasive species management system presented.

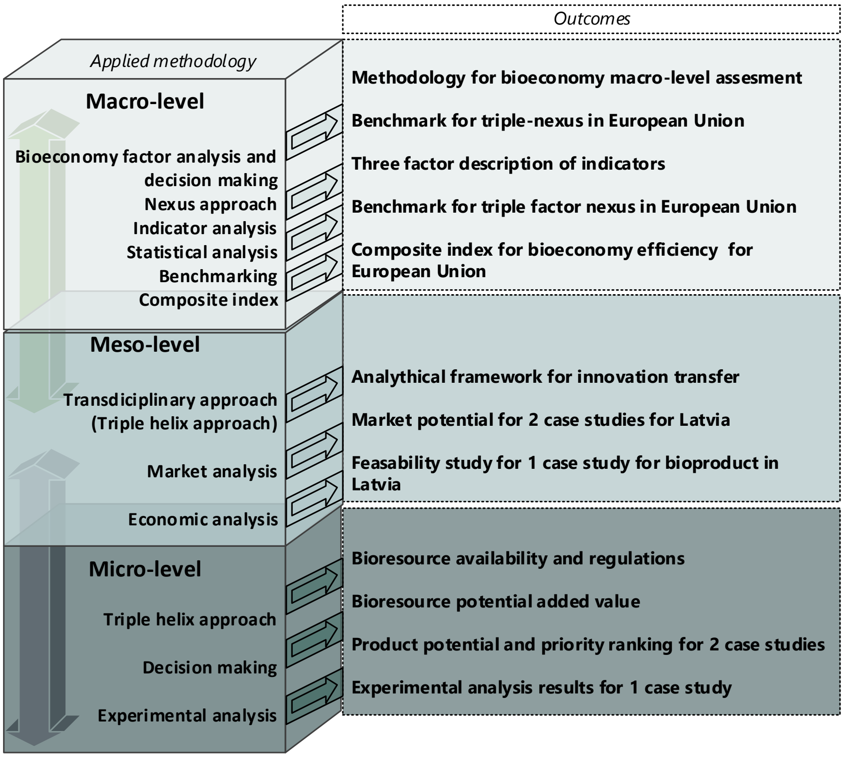

Fig. 1.1. Overall applied methodology of the Thesis and the outcomes.

Main outcomes of the applied methodology of the Thesis (Fig. 1.1) are the following: methodology for macro-level assessment; main factors identified and triple factor nexus presented for European Union; benchmark is expressed as a mathematical regression model; and a composite index has been created. For innovation transfer, analytical framework is created, market potential assessment for several cases performed, and feasibility study for early stage innovation presented. New invasive species management system has been created and validated by bioresource potential added value and experimental analysis. Another case of agri-industrial residue product potential and priority ranking is presented.

1.1. Macro-Level Assessment Research Methodology

Macro-level assessment methodology is based on top-down approach, as bioeconomy is stated to be bottom-up approach, there should be a concise assessment how to show bioeconomy efficiency, to measure bioeconomy in macro scale. Therefore, top-down analysis is performed, to find bottlenecks that should be overcome in order to measure bioeconomy with one index – bioeconomy effectiveness index.

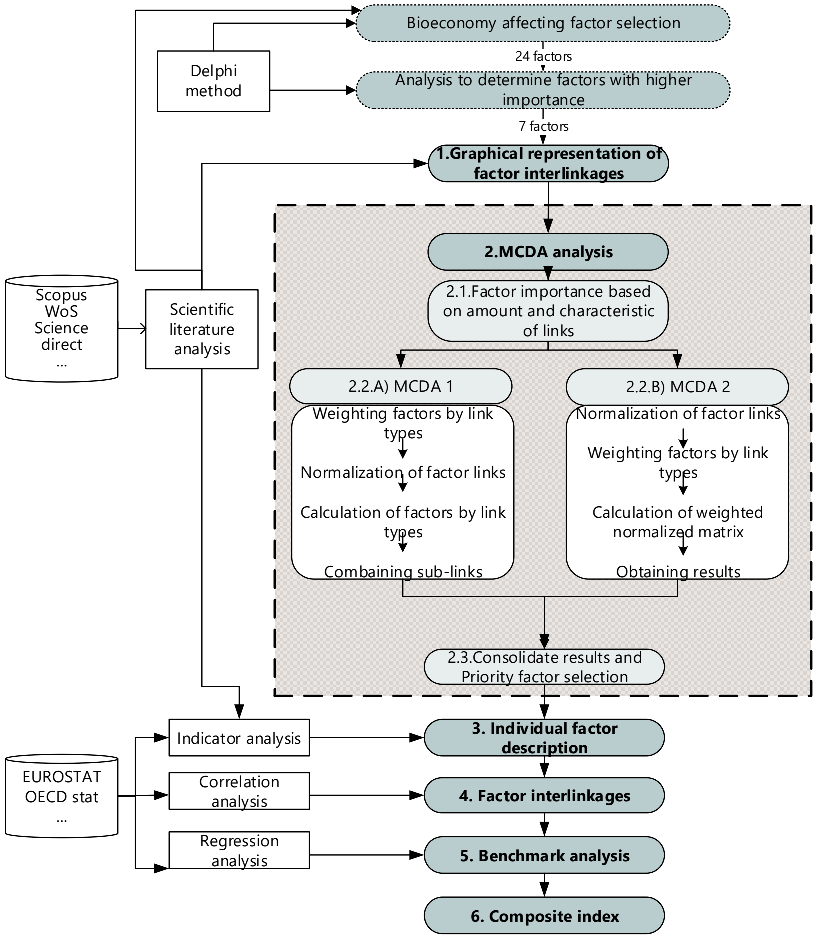

Fig. 1.2. Macro-level methodology.

Macro-level assessment methodology consists of five steps and is based on top-down approach, see Figure 1.2.

Step 1. Based on scientific literature analysis and by the use of Delphi method, seven primary factors were selected from a set of 24 bioeconomy affecting factors, and a graphical representation of factor interlinkages was built by determining whether the link is direct (represented with a straight line) or indirect (represented with a broken line) and whether it is an influencing or dependent link (represented with the direction of an arrow). Indirect links mean that more than two factors are involved in the linkage, therefore, the derivative has been reached through another factor or with more than two factors together.

Step 2. Multi criteria decision making analysis is applied as quantitative approach for determination of factors with the highest impact on bioeconomy development. This is a preliminary assessment and does not mean that other factors should be excluded from assessment; to the contrary, this assessment will only give an overall notion on which factors have the strongest impact on bioeconomy. As it is well known, different MCDA approaches give very different results [16], therefore, to get a better perspective, it is advised to use at least two MCDA methods for the same decision. The consolidated result for decision making is proposed. In this research two MCDA approaches are used: the technique for order of preference by similarity to ideal solution (TOPSIS) and analytical hierarchy process (AHP), which are two of the most commonly used MCDA analysis methods in the context of sustainable development [2].

MCDA analysis is conducted based on four criteria: direct influencing links, direct dependent links, indirect influencing links, and indirect dependent links. Values for seven factors (alternatives) are based on the number of linkages described. Link weights are based on assumptions, i.e., for both methods the weight of link strength is assumed to be 2 : 1, where direct links (both influencing and dependent) are two times more significant than indirect links (both influencing and dependent). As multi criteria decision analysis methods vary and often give slightly different results, a novel approach is used by creating a consolidated result between the two methods. If this methodology is used in other studies, more than two MCDA analysis methods can also be applied if necessary, as well as, different approaches can be used according to the specifics of the problem that needs to be solved.

Step 3. Individual factor analysis. To get an in-depth characterization of factors, each selected factor is analysed separately in the context of bioeconomy. Each of the factors is described through indicator analysis and grouped as environmental, economic, social or technological aspect indicator.

Step 4. The application of nexus approach with the aim to find a way to measure the link strength, e.g., by overlapping indicators that are related to bioeconomy influencing factors that could provide an insight and correlation between each two or more factors.

Step 5. Finding benchmarks that best characterise the linkage between two factors. Benchmark is expressed as mathematical regression models that characterize the link and its strength.

Step 6. Final step is the creation of composite index for bioeconomy efficiency.

1.1.1. Decision Analysis

Decision analysis can be applied to all level assessments.

Decision making is an important step in all level assessments therefore it is used at macro-level for factor link analysis and micro-level for levelling the biomass and for product selection according to priorities. In the Thesis two of the most popular decision analysis methods are used: TOPSIS and AHP.

Analythical Hierachy Process (AHP)

At the macrolevel, AHP is applied separately for each link type to get more consistent results.

For each sub-link type results are normalised and priority vector is obtained. Afterwards, the results of each alternative are summarized to acquire final results. AHP values are obtained by the division between link amounts to determine which factor is more important than others. That is the main difference in AHP calculations where the typically used importance, e.g., based on fundamental scales from 1–9, is not applied, but exact values are calculated in between criteria pairs instead.

Pairwise comparison is done for each sub-link type individually, where one weighted alternative value is divided with another weighted alternative value, gaining importance value for AHP matrix.

$$A_{im} = \begin{bmatrix} A_{11} & A_{12} & \dots & A_{1n} \\ A_{21} & A_{22} & \dots & A_{2n} \\ \dots & \dots & \dots & \dots \\ A_{n1} & A_{n2} & \dots & A_{nn} \end{bmatrix}, \tag{1.1}$$

where matrix A represents judgments (relative importance) of alternatives, where n is the number of alternatives being evaluated. Matrix A is built for each criterion separately, where $i = 1, \dots, m$ (in this case $i = 1, \dots, 4$).

After pairwise comparison, a normalization of values has been performed:

$$X_{ij} = \frac{A_{ij}}{\sum_{i=1}^{n} A_{ij}}, \tag{1.2}$$

where X_{ij} – normalized value, $i = 1, \dots, m$, $j = 1, \dots, n$; A_{ij} – pairwise matrix elements (alternatives), $i = 1, \dots, m$, $j = 1, \dots, n$.

Calculation of priority vector

$$W_{ij} = \frac{\sum_{j=1}^{n} X_{ij}}{n}, \tag{1.3}$$

where W_{ij} – priority vector, $i = 1, \dots, m$, $j = 1, \dots, n$; n – number of alternatives [97].

Technique of Order Preference by Similarity to the Ideal Solution (TOPSIS)

TOPSIS analysis method [98], which is based on Euclidean distance evaluation, gives result as closeness to the ideal solution. TOPSIS calculations can be found in author's previous work [99]. The preferable outcome (ideal solution) for all criteria is the maximum and anti-ideal for all criteria is the minimum amount. As stated previously, weights are identical for both methods.

Normalization of values were carried out by standardized form:

$$n_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}}, \tag{1.4}$$

where n_{ij} – normalized value; $i = 1, \dots, m$; $j = 1, \dots, n$.

Weighted normalized decision matrix is calculated as

$$v_{ij} = w_j n_{ij}, \tag{1.5}$$

where v_{ij} is weighted normalized value, $i = 1, \dots, m$; $j = 1, \dots, n$; and w_j is the weight of the j-th criterion, $\sum_{j=1}^{n} w_j = 1$.

Separation measures calculate the distance from the positive ideal and negative ideal solution:

$$d_i^+ = \sqrt{\sum_{j=1}^{n}\left(v_{ij} - v_j^+\right)^2}, i = 1, 2, \ldots, m, \quad (1.6)$$

where d_i^+ is distance to ideal solution.

$$d_i^- = \sqrt{\sum_{j=1}^{n}\left(v_{ij} - v_j^-\right)^2}, i = 1, 2, \ldots, m, \quad (1.7)$$

where d_i^- is distance to negative solution.

In the final step of the calculation of relative closeness to the positive ideal solution is performed as follows:

$$R_i = \frac{d_i^-}{d_i^- + d_i^+}, \quad (1.8)$$

where $0 \leq R_i \leq 1$, $i = 1, 2, \ldots, m$.

1.1.2. Construction of Composite Sustainability Index

Table 1.1

Grouping Indicators According to Their Impact on CSI [24]

Dimenssion	Sub-dimension notation, j	Sub-indicator's positive impact	Sub-indicator's negative impact
Economic	1	$I_{\text{act},1i}^+$ $i = 1, \ldots, n$	$I_{\text{act},1i}^-$ $i = 1, \ldots, n$
Social	2	$I_{\text{act},2i}^+$ $i = 1, \ldots, n$	$I_{\text{act},2i}^-$ $i = 1, \ldots, n$
Environmental	3	$I_{\text{act},3i}^+$ $i = 1, \ldots, n$	$I_{\text{act},3i}^-$ $i = 1, \ldots, n$
Technical	4	$I_{\text{act},4i}^+$ $i = 1, \ldots, n$	$I_{\text{act},4i}^-$ $i = 1, \ldots, n$
…	j_n	$I_{\text{act},ni}^+$ $i = 1, \ldots, n$	$I_{\text{act},ni}^-$ $i = 1, \ldots, n$

I_{act} is the actual value of an indicator (raw data), I_{min} is the minimim value from the data set of the specific indicator, I_{max} is the maximum value from the specific indicator's data set. Notation j represents the particular sub-dimension ($j = 1$ is economic dimension; $j = 2$ is social dimension, $j = 3$ is environmental dimension; $j = 4$ is technical dimension). Notation i represents the name of the specific sub-indicator of the particular sub-dimension.

$$I_{\text{N},ji}^+ = \frac{I_{\text{act},ji}^+ - I_{\text{min},i}^+}{I_{\text{max},i}^+ - I_{\text{min},i}^+}, \quad (1.9)$$

$$I_{\text{N},ji}^- = 1 - \frac{I_{\text{act},ji}^- - I_{\text{min},i}^-}{I_{\text{max},i}^- - I_{\text{min},i}^-}, \quad (1.10)$$

where $I^{\pm}_{\mathrm{N},ji}$ is the normalised value (positive +, or negative –) of individual indicator *i* for dimension *j*.

When weights have been assigned to each sub-indicator, the following step is aggregation of all the sub-indicators in each dimension. The calculation is performed using Eq. 1.11, where W represents the determined weight of the indicator and I_{N} is the obtained normalized value of the indicator.

$$I_{\mathrm{S},j} = \sum_{i}^{n} W_{ji} I^{+}_{\mathrm{N},ji} + \sum_{i}^{n} W_{ji} I^{-}_{\mathrm{N},i}, \tag{1.11}$$

where $I_{\mathrm{S},j}$ – weighted sub-indicator, in dimension *j*; *W* – weight of variable *i* in dimension *j*.

Then the final composite sustainability index is determined by the accumulated sum for each dimension with its corresponding weight. The calculation is done according to Eq. 1.12.

$$I_{\mathrm{CSI}} = \sum_{j}^{n} W_j I_{\mathrm{S},j}, \tag{1.12}$$

where I_{CSI} is complex index of alternative *I*.

The obtained sum of all the dimensions is the final CSI index that can be used for further comparisons in the research.

1.2. Meso-Level Assessment Research Methodology

The successful transition towards sustainable bioeconomy comes about through radical innovations that are promoted mostly by academics of universities and research institutions.

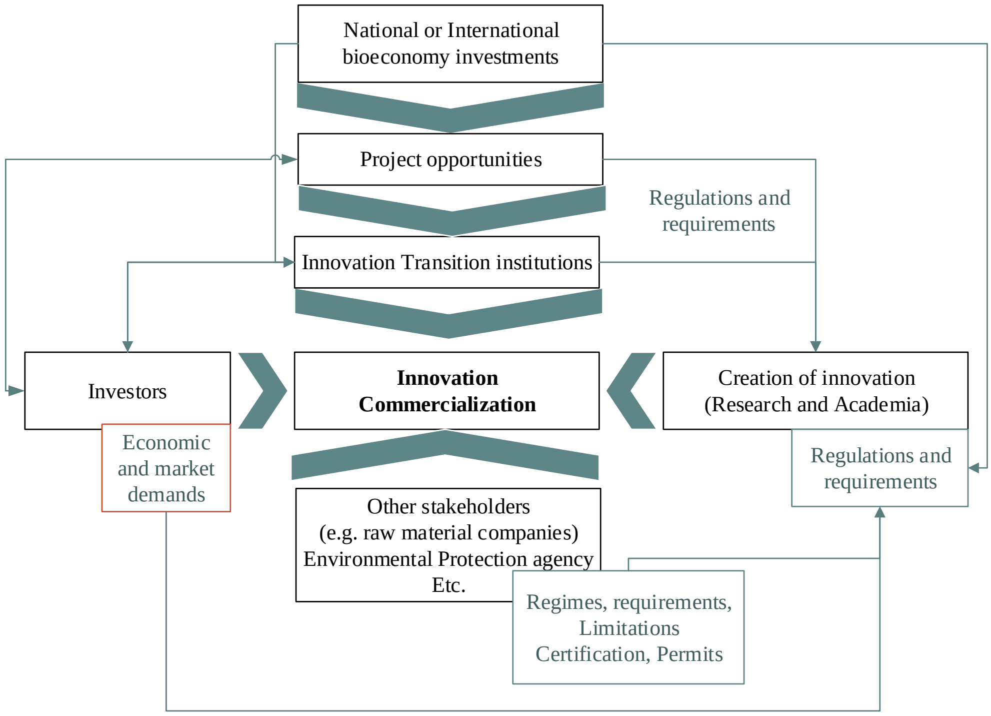

Fig. 1.3. General meso-level algorithm through transdisciplinary lens (created by author).

In Figure 1.3, general meso-level algorithm shows the importance of transdiciplinarity, where several stakeholders'(institutions') views, regulations and requirements should be taken into account for radical innovation transition to successful commercialization, for example the main interest of investors are economic justification and market opportunities, that are the base for successful product or technology commercialization. Innovation commercialization now is promoted by innovation transfer institutions that work as a bridge between investors (business thinking) and academia (science thinking) through projects that are funded by national or international stakeholders. From one point of view it is very useful for innovation commercialization and bringing together two differently thinking parties, but it comes with some requirements and challenges and trust from both sides. For example, if the requirement is to commercialize the technology or product with licence costs not less than 300 000 EUR, for academics it could be a challenge to adapt this product or technology so that the revenue from it is not less than investments made.

Meso-level assessment methodology is shown in Figure 1.4. For transdisciplinary analysis it should include scientific point of view and stakeholders' interests of meso-level assessment.

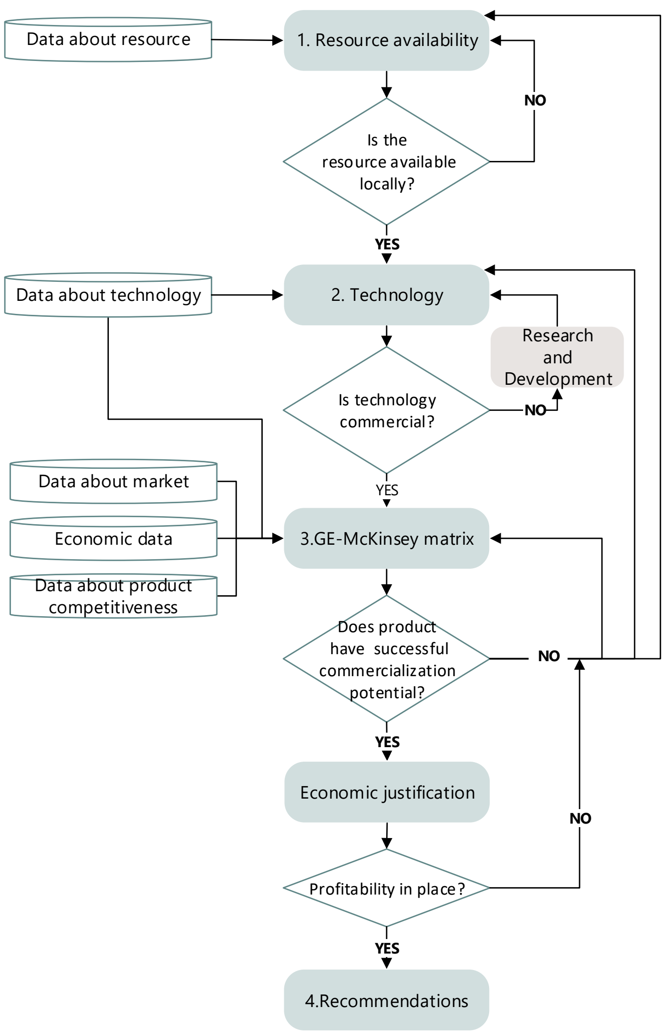

Fig. 1.4. Meso-level assessment algorithm.

Step 1. Resource availability is the first step to promote bioeconomy. Resources should be local and not dependent on import.

Step 2. Technology should be available on commercial scale even if it is innovative technology. If innovative technology is not yet in commercial stage it goes back to research and development (R&D) stage.

Step 3. Decision making matrix in this case is GE–McKinsey matrix that has been used for market assessments. Economic data and data about technology have been collected for calculations, as well as data about product competitiveness and data about the market. After obtaining the results, these data are placed in the matrix for decision making. A positive result from calculation does not always show the actual situation; use of the matrix visualization is typically necessary. Information sources for the matrix consist of scientific publications, existing plant data, and annual reports. Expert opinion, not including consumer surveys, can also be considered. Data analysis is carried out based on the collected data from information sources and shown in two dimensions (market attractiveness and product competitive advantage) on the GE–McKinsey matrix. The main data are collected from information sources such as scientific research papers or the subject company's data sources (excluding consumer surveys).

Step 4 is matrix result visualization and recommendations on further assessment on new product production in current location or country where local resources are available.

1.2.1. Market Potential Analysis GE–McKinsey Matrix

The methodology employed here (GE–McKinsey Matrix) uses nine modules or boxes to denote aspects of the market for potential new bioproducts. The methodology, see Figure 1.4, has been developed and proven on three existing products.

The methodology for the GE–McKinsey matrix has been modified to include considerations and constraints, such as environmental protection, required in the manufacturing process and product sustainability. Instead of the competitive position of the company it shows the competitive attractiveness of a particular product. After obtaining results, it is possible to gain an insight into market opportunities for the product.

A similar analysis can be made using the Boston Consulting Group matrix, which may be the best known planning framework. However, the GE–McKinsey matrix is newer and provides a more highly developed analysis with a broader range of factors. Basically, the GE–McKinsey matrix has been developed from the Boston Consulting Group matrix, as the latter was found not to be sufficiently flexible and had complexity issues as well [3]. The GE–McKinsey matrix is widely used for product portfolio management and in the analysis of competitive scenarios [4].

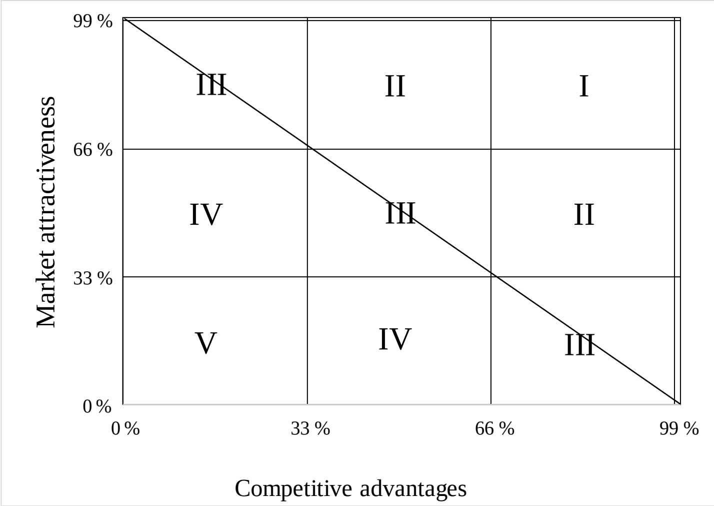

Fig. 1.5. "Market attractiveness – competitive advantages" matrix, or GE–McKinsey matrix [3], [4].

Figure 1.5 shows that products that are above the diagonal line are high performers with commercialization potential; these are the products that a company needs to focus on. Products that fall below the line need to be further analysed and improved until they appear at least above that line. Otherwise they should be discounted or in some cases discarded. Products can be also evaluated based on the quadrant in which they are located. A product in quadrant I is worth investing with no further calculation or assessment and may be marked as a product leader. Products in quadrant II have potential for growth and it may be advisable for the company to invest in them if improvements can be found and implemented. Products in quadrant III are in passably attractive markets but before proceeding need to be evaluated further to see if there are opportunities for biorefining. Quadrant IV represents weak markets; it is not advisable to invest in those products. Quadrant V products should be discarded [3], [5].

The advantage of this matrix is that it takes into account a wider range of factors than the Boston Group matrix and is visually easier to understand. GE–McKinsey matrix has wider dimensions because it has nine fields, three *x* three grids. For comparison, the Boston Group matrix has only two *x* two grids [3], [6].

Market attractiveness may be calculated as follows:

$$M_{\mathrm{a}} = \frac{Zk}{100}, \tag{1.13}$$

where M_{a} – market attractiveness total score; Z – estimated rating score.

$$k = \frac{100}{f \cdot B_{\mathrm{max}}}, \tag{1.14}$$

where k – coefficient; f – number of factors; B_{max} – max rating score.

The relative competitive advantage indicator is calculated by comparing a product with its strongest competitor and is expressed by equation

$$R = \left(\frac{B}{B_{\mathrm{comp}}} - 1\right) 100, \%, \tag{1.15}$$

where R – relative indicator of product competitive advantages; B – new product score estimation; B_{comp} – score estimation of strongest competitor.

1.3. Micro-Level Assessment Research Methodology

Micro-level assessment methodology algorithm is described and showed in Figure 1.6.

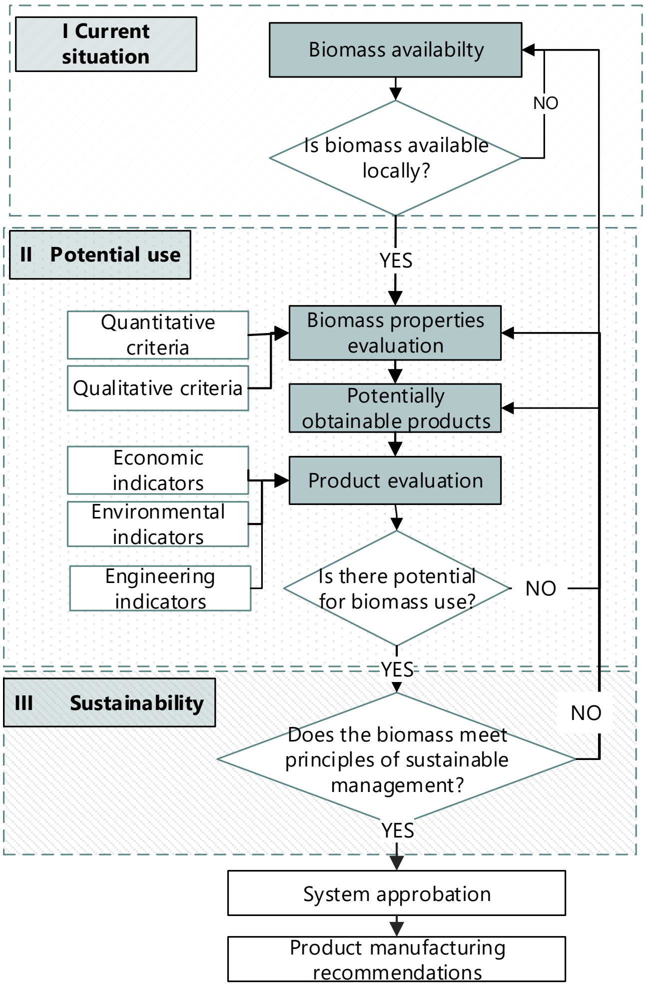

Fig. 1.6. Micro-level assessment algorithm.

Micro level assessment is based on bioresource availability locally, potential value assessment, and priority selection as decision analysis. Experimental analysis is done for solid biofuel potential.

MCDA method technique of order preference by similarity to the ideal solution (TOPSIS) was used to prioritize underused bioresources occurring in Latvia according to their valorisation aspect. In this case the ideal solution is the species that show priority for further assessment of impact on ecosystem services, to biodiversity, social and economic impact (high, moderate of low). The alternatives are the invasive or potentially invasive alien plant species detected within a country.

1.3.1. Experimental Analysis for Solid Biofuel Potential Assessment

Methodology is focused on the selection of raw materials that can be used as a solid biofuel and are not used in forestry, agriculture, aquaculture, and food industries. Sustainability criteria are determined to select appropriate materials and binders, as well as to find low cost and preferably residue/waste bioresource. At first, samples were prepared with and without binders. Binders were used in the same proportion for each sample. Determination of main solid biofuel parameters (ash and moisture content, calorific value) allows to evaluate the quality of raw material, binder and mixed pellet. Materials with higher calorific value, lower ash and moisture content were selected for further testing. In further sample preparation different binder proportions (10 wt. %, 30 wt. % and 50 wt. %) are used. Tested parameters are the same as previously. If calorific value increases, ash content remains the same or decreases and moisture content is lower than 10 wt. %, then solid biofuel and binder classifies as justified. If the changes are significant and without clear tendency, more samples need to be tested in different proportions to find the optimal proportion and results.

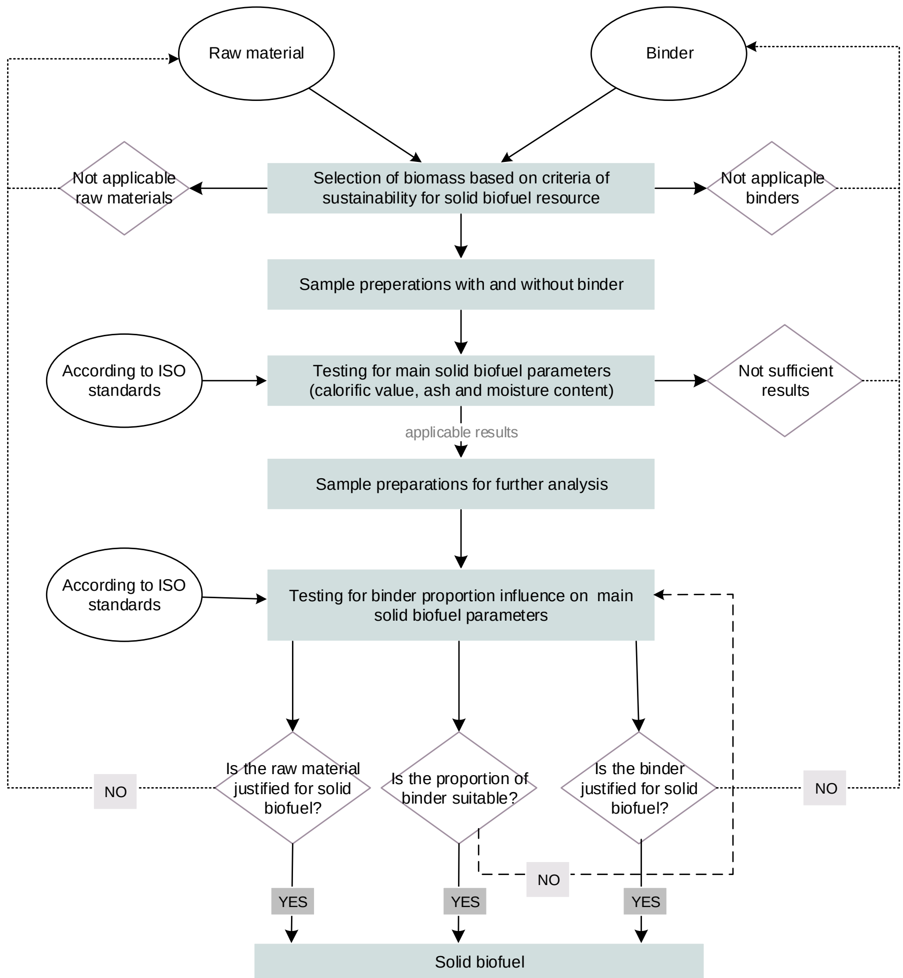

Fig. 1.7. Algorithm for new resource solid biofuel validation.

Figure 1.7 shows the methodology algorithm for resource validation as solid biofuel. The steps and criteria selected restrict the selection of biomass and biofuel. The methodology case study is conducted on invasive species.

After selecting raw materials and binders by criteria of sustainability, two raw materials and two binders have been selected for sample preparation and further analysis.

Criteria of sustainability for raw material and binder selection for solid biofuel are as follows:

- non-woody resource;
- non-agricultural resource;
- resource that is not used in aquaculture;
- no fertilizer or additional water needed;
- resource that is not used in food industry;
- bioresource (not fossil fuel);
- residue/waste unused elsewhere;
- available/local resource (corresponds to geographical location and climate zone)
- low cost resource;
- resource is not used in the production of high added value product in the specific location (country);
- resource has positive impact on environment and climate.

The main biofuel characteristics was tested according to ISO standards on biofuel testing: ash content, moisture content and calorific value.

Ash content was calculated according to Eq. 1.16:

$$A_{\mathrm{d}} = \frac{(m_3 - m_1)}{(m_2 - m_1)} \cdot 100 \cdot \frac{100}{100 - M_{\mathrm{ad}}}, \tag{1.16}$$

where m_1 – mass of empty dish, g; m_2 – mass of dish plus the test portion, g; m_3 – mass of dish plus ash, g; M_{ad} – moisture content of the test portion used for determination of ash content, wt. %.

The result is calculated to two decimal places and the mean value is rounded to the nearest 0.1 % for reporting [112]. Maximum acceptable relative difference between results of ash content larger than 1 % is 10 %.

Moisture content

The sample was kept in air-tight plastic bags (according to EN 14778) and nominal top size was reduced below 1 mm [113]. The moisture content of general analysis sample has been determined according to ISO 18134-3. The sample was dried in a drying oven at 105 °C. Dishes were from non-corrodible and heat-resistant material covered with a well fitted lid [113].

It was assumed that the sample does not lose moisture during preparation of the test portion. The mass of test portion was in range 0.8–1.1 g.

After sample preparation, an empty and clean weighing dish with its lid was dried at (105 ± 2) °C and then cooled to room temperature in a desiccator. Then the test portion was put in dried dishes and dried without its lid at (105 ± 2) °C for 1 hour. One heating period lasted for 60 min. Each test portion was dried three times and each sample was tested in triplicate.

$$M_{\mathrm{ad}} = \frac{(m_2 - m_3)}{(m_2 - m_1)} \cdot 100, \tag{1.17}$$

where m_1 – mass of the empty dish plus lid, g; m_2 – mass of the dish, lid, and test portion before drying, g; m_3 – mass of the dish, lid, and test portion after drying, g.

For repeatability the result of triplicate determinations did not differ more than 0.2 % absolute [113].

Calorific value

Calorific value analysis was performed according to ISO 18125 standard. Experiment was done at isoperibolic conditions, reference temperature was 30 °C [114].

Calculation of gross calorific value for dry mass (at constant volume):

$$Q_{\mathrm{a}}^{\mathrm{d}} = H_0 - \frac{Q_{\mathrm{N,S}} + Q_{\mathrm{S}}}{m}, \tag{1.18}$$

where $Q_{\mathrm{a}}^{\mathrm{d}}$ – gross calorific value at constant volume, J/g; m – mass of sample, g; $Q_{\mathrm{N,S}}$ – correction of heat, considering formation of nitric acid, J; Q_{S} – correction of heat, considering formation of sulphuric acid, J; H_0 – gross calorific value of the analysed fuel, J/g.

Repeatability limit for non-wood solid biofuels is 140 J/g [114].

$$Q_{\mathrm{S}} = 57 S^{\mathrm{d}} m_{\mathrm{s}}, \tag{1.19}$$

where S^{d} – sulphur content in the analysed sample (on dry basis), %.

$$Q_{V,\mathrm{dr,d}} = Q_{V,\mathrm{gr}} \frac{100}{100 - M_{\mathrm{ad}}}, \tag{1.20}$$

where $Q_{V,\mathrm{gr,d}}$ – gross calorific value of dry mass at constant volume, J/g; M_{ad} – moisture content of general analysis sample, wt. %.

$$Q_{p,\mathrm{net,d}} = Q_{V,\mathrm{gr,d}} - 212.2 H^{\mathrm{d}} - 0.8\left(O^{\mathrm{d}} + N^{\mathrm{d}}\right), \tag{1.21}$$

where $Q_{p,\mathrm{net,d}}$ – net calorific value of dry mass at constant pressure, J/g; H^{d} – hydrogen content in the analysed sample (on dry basis), wt. %; O^{d} – oxygen content in the analysed sample (on dry basis), wt. %; N^{d} – nitrogen content in the analysed sample (on dry basis), wt. %.

$$q_{p,\mathrm{net,ar}} = q_{p,\mathrm{net,d}}\left(1 + 0.01 M_{\mathrm{ar}}\right) - 24.42 M_{\mathrm{ar}}, \tag{1.22}$$

where $q_{p,\mathrm{net,ar}}$ – net calorific value for sample as received at constant pressure, J/g; M_{ar} – total moisture content, wt. %.

2. RESULTS

2.1. Results of Bioeconomy Macro-Level Analysis

The transition to sustainable bioeconomy with a customized approach would speed up its development and make it more targeted. There is still no common international method for determining, measuring and comparing the extent of sustainability. The aim of this task is to develop a methodology for the assessment of bioeconomy influencing factor interlinkages, and creation of benchmarks through a top-down approach. The main output is the assessment of factor interlinkages that could be further used for composite sustainability index creation. A case of triple factor nexus is presented: policy, research and innovations and technology nexus for European Union countries. As a result, the empirical model presents the mathematical description of policy, research & innovation and technology link benchmark.

Factor analysis

Altogether 24 bioeconomy affecting factors had been obtained in previous research. After expert evaluations and application of Delphi method, seven primary bioeconomy affecting factors and their linkages were identified (Fig. 2.1). Linkages were also based on scientific literature and discussed. Linkages are described as direct or indirect based on how they are affecting the factors. In future research it is advised to use triple or quadruple factor link assessment to gain more insight into linkage characteristics based the factors that the link is connecting.

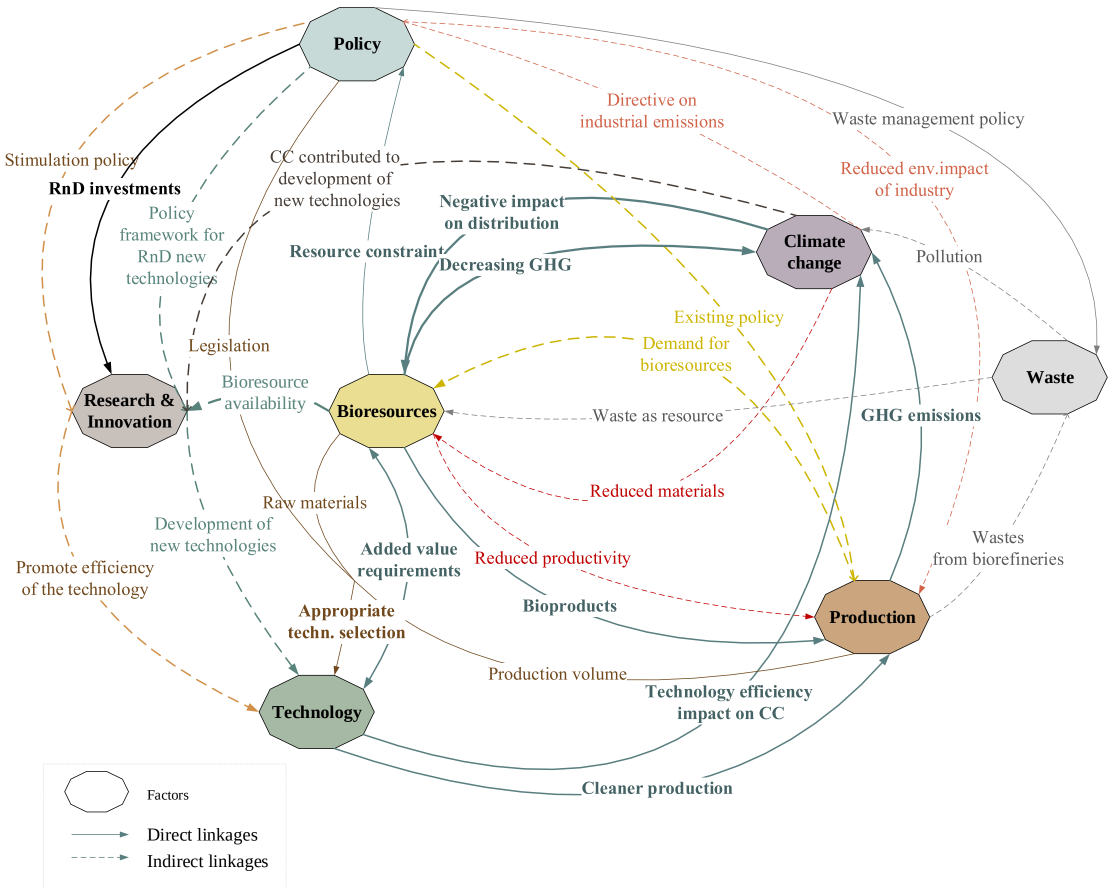

Fig. 2.1. Graphical representation of seven bioeconomy factors interlinkages.

Modern technologies have impact on environment; energy efficiency has one of the more noticeable effects [7]. The industry has come a long way from burning coal with efficiency as low as 0.5 % [8] to around 90 % efficiency in the last decades [9]. In addition, technologies play an immense role in industry by allowing to produce bioproducts from raw materials, thus creating strong links between bioresources, technologies, and bioproducts [10]. Preference for specific technology is impacted by production volume and raw materials used, as well as regional legislation [11].

Policy has a strong role in technological development as strategic incentives to research and development leads to the improved production efficiency of technologies. Adopting these technologies in new and existing production plants could lead to growing demand for biomass feedstock [12]. Due to existing legislation it is to be expected that demand for biomass feedstock for production will indeed grow in local, and even at the EU level [13] reducing the negative impact of production on climate [14]. Nevertheless, biorefinery causes pollution in form of gas, liquid waste, and solids [15].

One of many negative aspects of the climate change is altered temperatures and water cycles [16] leading to change of bioresource distribution in region [17]. Popular example of this negative effect on industry is the predicted decrease in coffee bean productivity [18].

Despite the fact that climate change negatively impacts industry, specific policies aimed at reduction of industry's negative impact on climate need to be implemented [19]. These policies are made to endorse innovations that prevent industrial emissions, including pollution [20].

Fossil fuel burning releases the carbon sequestered millions of years ago back into the atmosphere, hence increasing the amount of carbon in the active carbon cycle [8]. To slow down the climate change, fossil resources would need to be completely replaced by bioresources [21]. This would be an immense commitment from industry's part, as demand is dictating the supply. Demand not only dictates the amount of available bioresources but also stimulates the development of new greener technologies [22]. Unlike fossil resources, bioresources vary in composition, requiring more variable technologies demanding a more flexible approach form industry [13]. In addition, various biomass types lead to different products with varying value per ton of raw material [12].

Recognizing the crucial role of research and development in innovative technology development [12], the EU allocates considerable amount of resources to promote research and development of biotechnologies [13].

Main nexus identified from graphical representation linkages (Fig. 2.1) are: policy – research and innovations – technology; production – waste – climate change; production – waste – bioresources; policy – production – bioresources; technology – production – climate change; climate change – policy – production; policy – technology – production – bioresources; climate change – bioresources – production.

MCDA for all seven selected bioeconomy factors is performed with AHP and TOPSIS methods. AHP and TOPSIS methods are two of the most used MCDA methods [23]. Matrix is normalized using the vector normalization method and weighted accordingly. Distances till positive and negative solutions by Euclidean distance helps to rank the alternatives [24].

Assumptions made on the link type strength are included in both analysis methods (AHP and TOPSIS). Both direct links (direct influencing and direct dependent) are assumed to be twice as important as indirect links (indirect influencing and indirect dependent). Therefore, weights are 1/3 (or 0.33) for direct links and 1/6 (or 0.17) for indirect links.

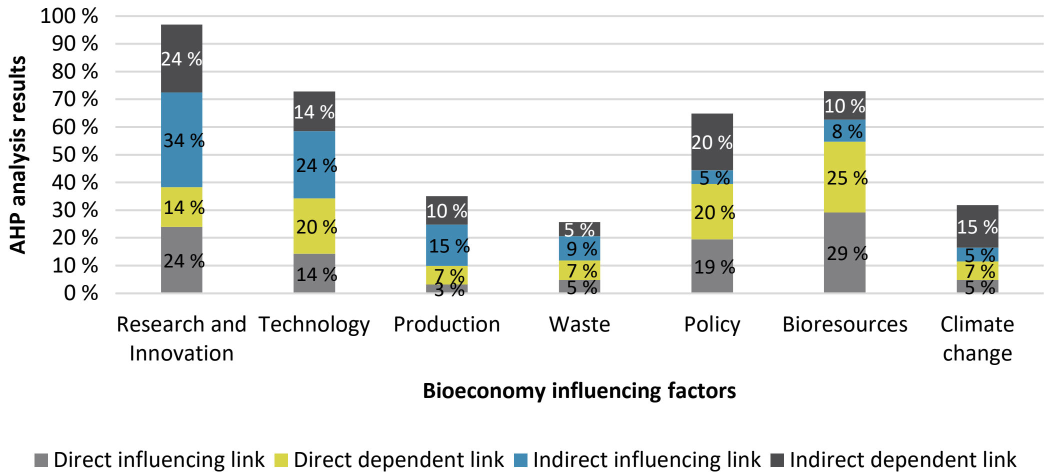

Fig. 2.2. AHP scores for factors based on link type.

From evaluation in Figure 2.2, it is seen that there are more indirect links than there are direct linkages between factors. For example, for research and innovation the largest share of the AHP analysis result is due to indirectly influencing links, so it can be understood that this factor is more of an instrument (driver) for bioeconomy development and works in close connection with other factors. The highest share of direct links is for bioresources, which is a factor that bioeconomy is based on. Policy and technology factors in AHP analysis also show great impact.

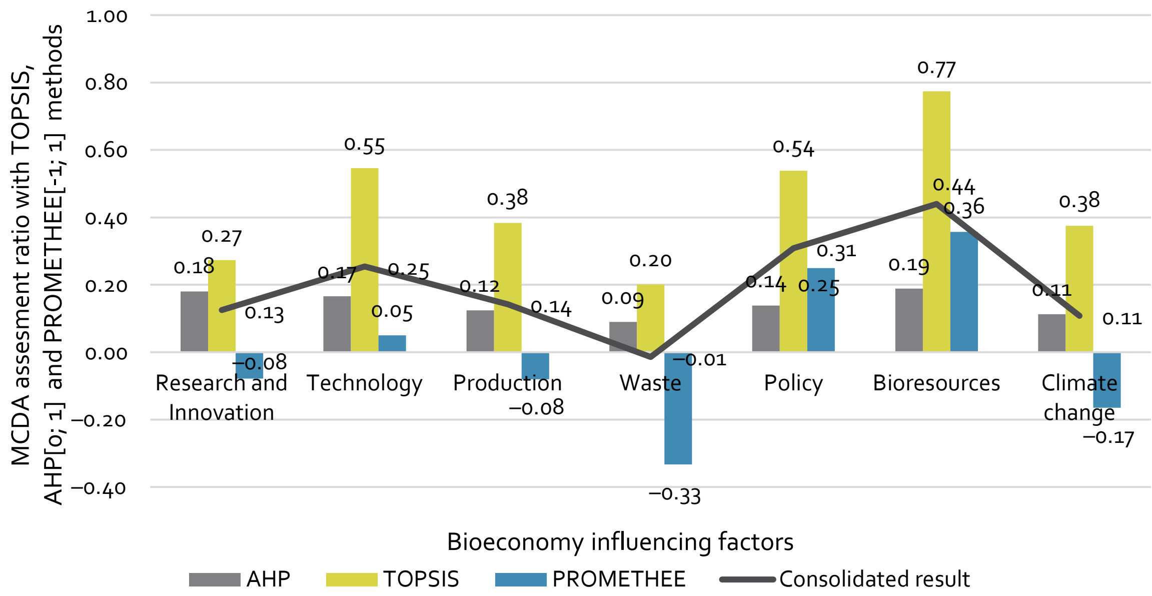

Fig. 2.3. MCDA analysis results for seven bioeconomy influencing factor importance based on their interlinkages.

Figure 2.3 shows the final results from both methods that differ based on the approach used. After a pairwise comparison (AHP), it was determined that the highest impact is for research and innovation, bioresources and technology, that can be confirmed by bioeconomy's definition as knowledge based and bio-based economy [25], and that in 2012, biotechnology was set as priority driver for bioeconomy development [26]. PROMETHEE analysis shows the greatest impact on bioresources, policy and technology. Although according to the TOPSIS analysis, bioresources have the highest score, technology and policy factors are also important. Bioresources play an important role in bioeconomy, as they are based on biomass and its sustainable use. Technology factor has high results in both methods, as it ensures sustainable use of resources as well as provides a more effective use and development of new technologies and bioproducts. In TOPSIS analysis, the policy factor has stronger results (second highest score between the alternatives) than research and innovations (6th highest score), and vice versa in AHP analysis method. Still, if we look back on interlinkages between these factors (Fig. 2.1), policy has indirect linkages through research and innovation that lead to technology factor. Therefore, it is proposed to take into account consolidated results when selecting priorities for further assessment on factor analysis and linkage selection.

Interval scales for TOPSIS analysis results varies from 0.2 (waste) to 0.77 (bioresources), and AHP analysis results vary from 0.09 (waste) to 0.18 (research and innovation), PROMETHEE varies from –0.33 (waste) to 0.36 (bioresources).

2.1.1. Triple Factor Nexus in European Union Bioeconomy Through Indicator Analysis

Research and innovation factor characteristics

Technology transfer organisations is the way how to bridge the gap between industry and academics [27]. But countries and regions that rely on transnational science and technology transfer organisations to advance the development of new bioproducts [17] should also consider governmental support.

There are two stages for transition to bioeconomy innovation: incremental and gradual innovations (through new products and processes) and implementation of diverse, radically new and disruptive innovations [25], [28].

For an effective transition to sustainable bioeconomy there is a need for the second type of innovations. This means that it will take radical innovations to make a global change towards desirable goals. This includes redesigned business models, reconfigured supply chains, setup of new value chains, such as development of new sustainable products and technology's needs, and knowledge and skills outside existing fields of expertise. Universities and research institutions are especially conceived as cornerstone to accomplish these radical innovations [25], [28].

Innovations can be described by type of innovation [29], stage of innovation development, technological readiness level (TRL) of innovation, extent to which innovations are disruptive or radically new [25], [30], level of complexity in the knowledge base for the innovation development [25], degree of cooperation between different actors in innovation development [28], level of complexity in the policy framework (European Commission Bioeconomy

Strategy 2012), and level of nonlinearity in the innovation development. "HORIZON 2020" has been one of the main instruments for promoting innovations in bioeconomy [25], and now it can be seen how efficiently that has worked.

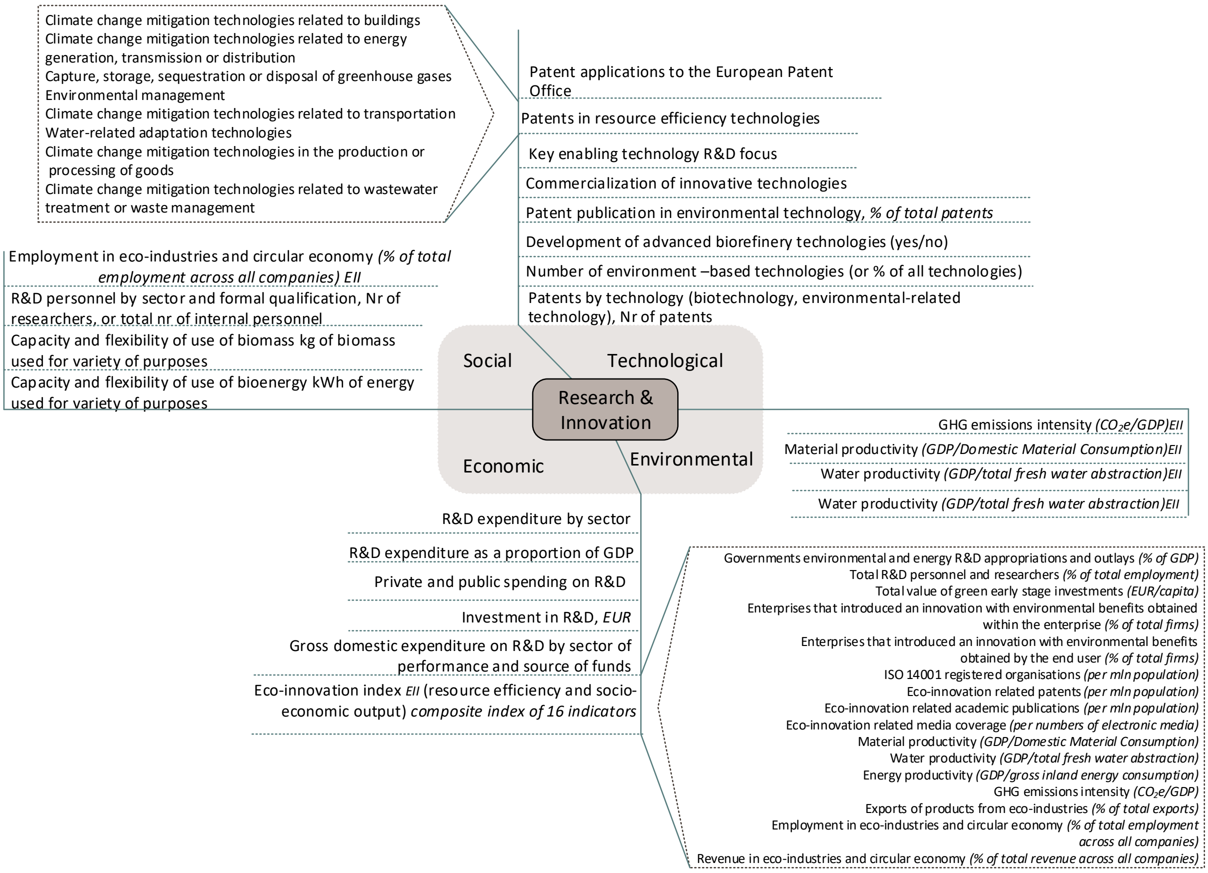

Fig. 2.4. Indicators that characterize research & innovation factor in bioeconomy context.

Figure 2.4 shows main indicators of research and innovation factor where two of the indicators have been explained in more detail by sub-indicators: patents in resource efficiency technologies and eco-innovation index (EII).

Policy factor characteristics

Policy is defined as a general set of actions and measures that are planned and set at the highest level of management and which include approved attitudes and regulations that must be followed when managing the operations of an organization [31]. Another policy understanding states that "a policy is a statement of intent to change behaviour in a positive way, while an [policy] instrument is the means or a specific measure to translate that intent into action" [32], [33].

Policy is one of the strongest and most significant factors that influences the implementation of sustainable bioeconomy. Bioeconomy development in a country depends on its political system and preferred policy instruments [34]. The EU Bioeconomy Strategy (2012) and its updated version (2018) [27] both emphasize the significance of policy for the development of bioeconomy.

The general types of policy instruments are: constraining and control measures, innovation promotion, product pricing mechanisms, information measures, enabling actors, and supporting investment [33].

Policy interventions may enable transition to sustainability and bioeconomy, but no single policy can ensure full systemic implementation of such transition [19]. A combination of various policy instruments is required to ensure the development of bioeconomy [12]. The policy instruments that are intended to promote the development of bioeconomy can generally be classified into four groups:

- legal, i.e. necessary changes in regulations and/or quality standards to allow and advance the sale of bioproducts;
- support for voluntary initiatives and requirements for public sector regarding implementation of biological waste collection;
- providing financial incentives for private investments in biorefineries (e.g. green certificates or feed-inn tariffs);
- public financial support for research and development [12].

Referring to the latter two groups of instruments, policy is related to the production and research and innovation, as the subsidies prescribed by a bioeconomy enhancing policy are commonly directed towards industry or research and innovation.

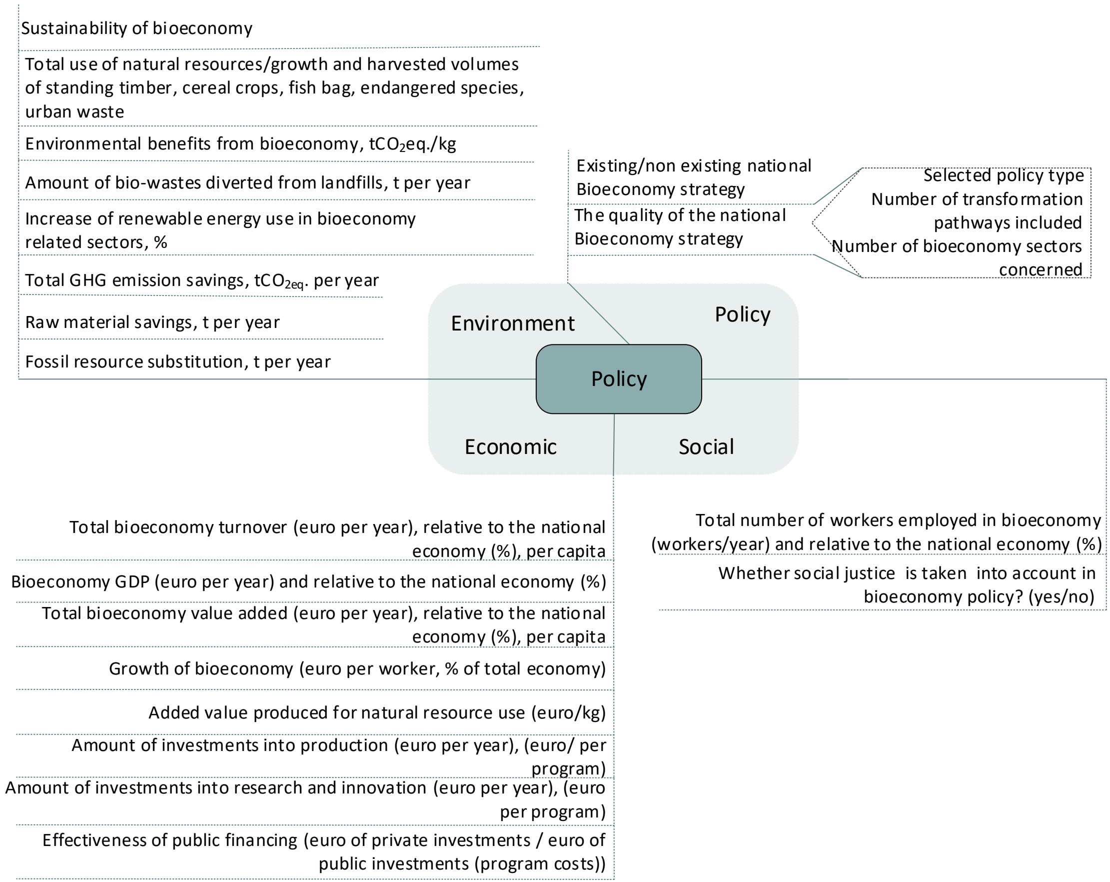

Fig. 2.5. Indicators that characterize policy factor in bioeconomy context.

By providing performance measurement, reporting and communicating to stakeholders, policy indicators help ensuring consistent and transparent consideration of sustainability within public policy [35]. Indicators that can be used for assessment of bioeconomy policy are those that characterize bioeconomy development. Figure 2.5 provides a graphical summary of indicators related to policy factor. Better indicator performance as a result of the implemented policy would prove the effectiveness of the policy, while no change or even decrease of indicator performance indicates inefficiency of applied policy.

Regarding policy instrument assessment, another aspect to consider is that various countries may have preference for different policy measures. Nevertheless, policy effectiveness should be assessed in respect to the chosen indicator, not based on what type of instruments are used [33] and longevity of certain policies [36], for instance, change of a left-wing government to a right-wing one might affect the policies.

Technology factor characteristics

Technologies are one of the main pillars of bioeconomy. Technologies bridge the gap from innovations to production and from unused or underused biomass to bioresources. Technologies include environment-related technologies, that allow to mitigate climate-change, biotechnologies and existing technology improvements that either solve the possibility to use biomass that otherwise could not be collected, or help advancing resource use efficiency.

One of the greatest emphasis of the technology factor in the context of bioeconomy is on biotechnologies. By collecting a list of biotechnology definitions, OECD has made one single statistical biotechnology definition: "The application of science and technology to living organisms, as well as parts, products and models thereof, to alter living or non-living materials for the production of knowledge, goods and services" [37]. Biotechnology has an important potential not only for economic development, but also for bioeconomy development [38]. Biotechnology cannot be advanced without knowledge, therefore there is a strong link to education and research institutions. As the main result of the development of technologies are patent applications, there should be a correlation between promotion of patent production at a local level as well as at international level to succeed in technology commercialization [38].

Technology indicators showed in Figure 2.6 are derived from OECD statistics as key indicators for technology (biotechnology). The number of active biotechnology firms in Latvia (including medical biotechnology, environmental biotechnology, industrial biotechnology, and agricultural biotechnology) according to the data that are available in OECD database for the last 2 years (2016 and 2017) is 9 and 12 accordingly [39]. That is the smallest amount in respect to the other countries for which data has been provided. However, in order to see actual situation, normalization should be applied.

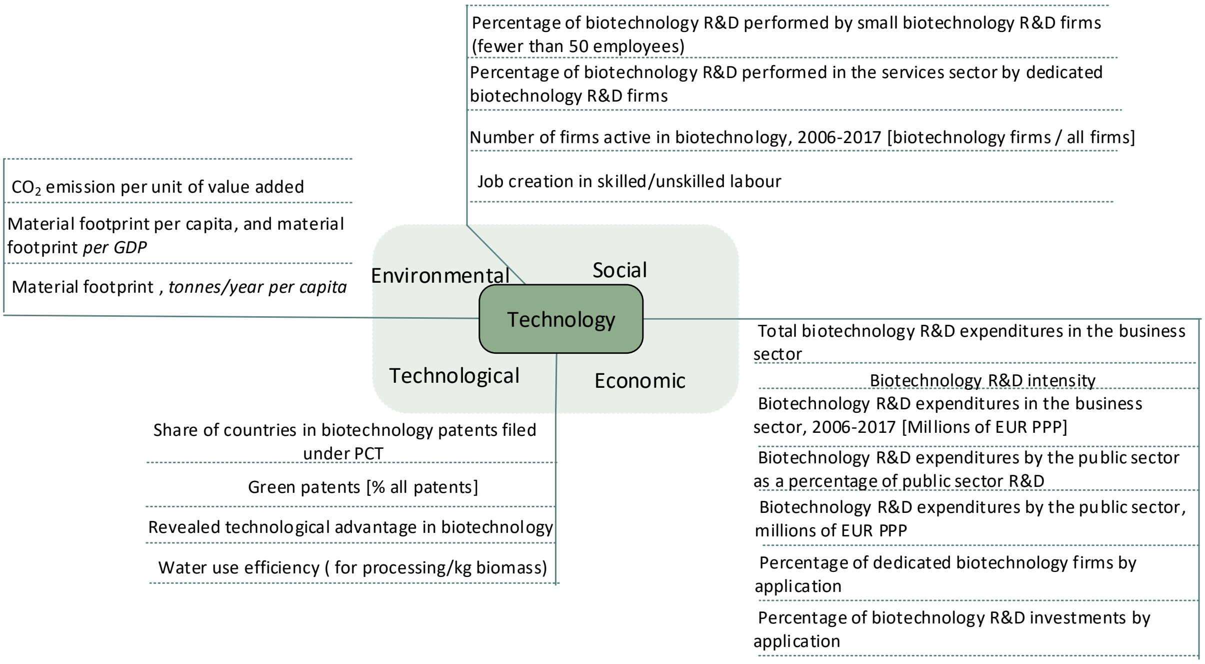

Fig. 2.6. Indicators that characterize technology factor in bioeconomy context [39], [40].

2.1.2. Benchmark for Triple Factor Nexus: Policy, Research and Innovations and Technology

Effective policy framework is imperative in order to ensure innovation and the development of new technologies and production methods. In [12] and [19] it is stated that R&D investments are crucial for the development of innovative technologies. In [12] it is also stated that technology and machinery knowledge and organisation of biomass logistics are required for the development of bio-based solutions.

Maes and Van Passel [12] explain the dynamic relationship between policy, innovation, technology, production and bioresource factors. A stimulation policy that provides incentives to research and development would promote improved production efficiency of the technology, which would in turn result in installation of those technologies in existing and new production plants. Sequentially, the requirements of the biomass feedstock would grow. Resource constraints are actually one of the main concerns in [12].

One indicator that is clearly overlapping between policy and research and innovation factors is investments in research and development. Countries are committed to significantly increase public and private R&D expenditures and the number of researchers by 2030 as part of Sustainable Development Goals [41]. In more detail, the dynamic loops of R&D expenditure and dynamics of innovation diffusion and technology adaption are described in [42]. Environmental policy has an effect on technological innovations. It can be manifested through tax measures or quota obligations with an impact on patent activity [43]. Patent data helps to examine eco-innovations across and suggestions for future policy. Resource (input) indicators are R&D expenditures and personnel (in terms of knowledge acquisition), R&D intensive goods or expenditure for licenses. The output indicators for R&D results are patents. Patent data is more commonly used as output indicator and key measure of innovations [43]. Policy framework should search for optimal solution on innovation rate and direction. Market-based instruments may affect technological trajectory of economy. The use of subsidies in support of environmental R&D could be in the form of grants or tax credits [44].

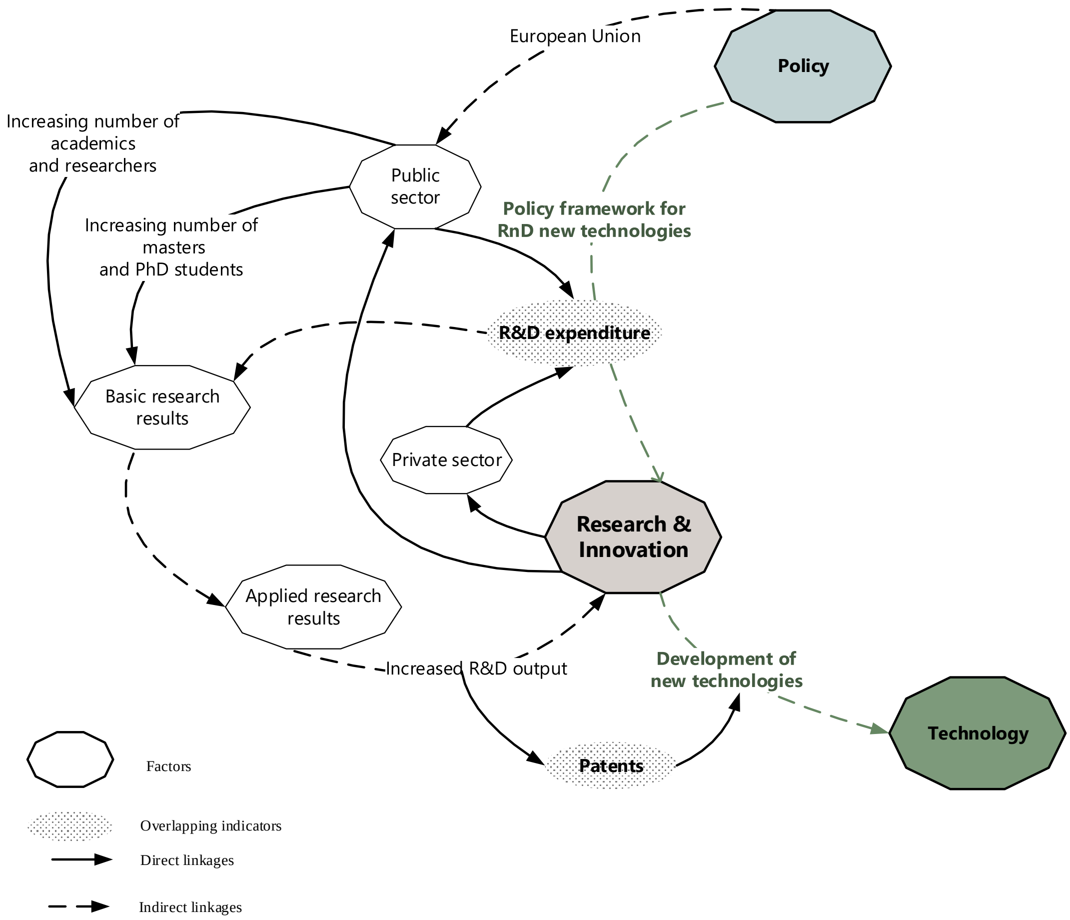

Fig. 2.7. Triple factor nexus: policy, research and innovation and technology.

Looking at graphical representation in Figure 2.7, the connection between policy and research & innovation goes through policy framework for new technologies and can be measured as R&D expenditure (public sector (government) further connects research & innovation to technology as the development of new technologies (that can be measured with patent applications). Assessing the nexus in-depth, there are more additional factors, that ensure the existence of these linkages as presented in Figure 2.1.

The indicator of this link coincides with Sustainable Development Goal 9 (SDG9) [45], therefore it is considered as a strong link towards bioeconomy sustainable development.

Benchmark analysis is one of the effective analysis methods for description of bioeconomy performance at a country level. In this case, the existing performance in each European Union country is analysed and compared with the practice in leading EU countries to adapt or improve the existing policy, moving towards sustainable bioeconomy development. In triple factor nexus, two indicators that have been selected for the assessment of one of the possible link benchmarks are R&D expenditures (that characterize the link between policy and R&D) and the number of patent applications (that characterize the link between R&D and Technology).

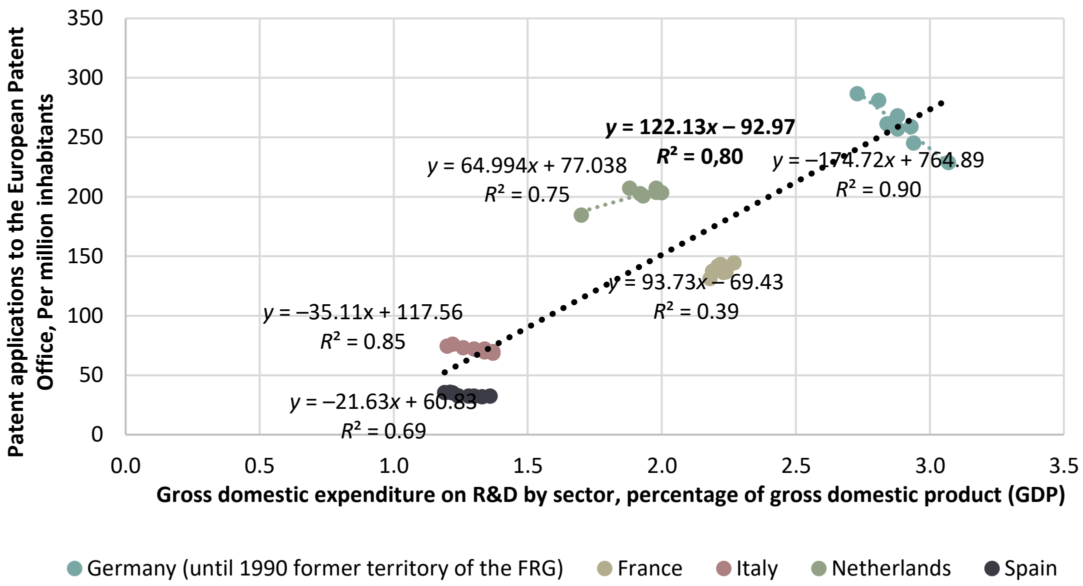

Fig. 2.8. Benchmark for the policy, research & innovation, and technology link.

Top countries[1] over the benchmark (which is set as European Union 28 country average) in patent applications to the European Patent Office (SDG_9_40; Eurostat) attributed to the gross domestic expenditure on R&D by sector (SDG_09_10; Eurostat) are selected for link indicator benchmark analysis. For these top countries (Germany, France, Italy, the Netherlands, and Spain) data correlation is good at intra country level, as well as at inter country level (Fig. 2.8), providing European Union with the best practice benchmark with strong correlation (R = 0.8).

The empirical model (2.1) presents the mathematical description of policy, research & innovation, and technology link benchmark.

$$P = 122.13c - 92.97, \tag{2.1}$$

where P – patent indicator: applications to the European Patent Office per million inhabitants; c – gross domestic expenditure on R&D by sector.

With the use of this empirical model, each country can calculate their situation, based on the benchmark.

2.1.3. Bioeconomy Efficiency Index

The data limitations regarding bioeconomy assessment are also related to the fact that bioeconomy related metrics for added value, turnover, and employment are only available in a particular database [46], which has been compiled by the Joint Research Centre of the EU, but there are no official bioeconomy specific databases in the national and European statistics. However, the most recent data in this database are for 2015, thus there is no possibility to develop the bioeconomy efficiency index for more recent years for which the indicators are available from other databases. For the index presented in Figure 2.9, average indicator values

[1] The United Kingdom is excluded from the analysis due to Brexit and in order to provide reliable future benchmark.

between 2011 and 2015 were applied, as it was identified that annual data for some indicators (especially for biotechnology patents) are very variable.

The results are obtained by developing an MS Excel based calculation model. Equal weights are applied for all seven indicators. The results of the proposed bioeconomy efficiency index for EU28 countries are presented in Figure 2.8.

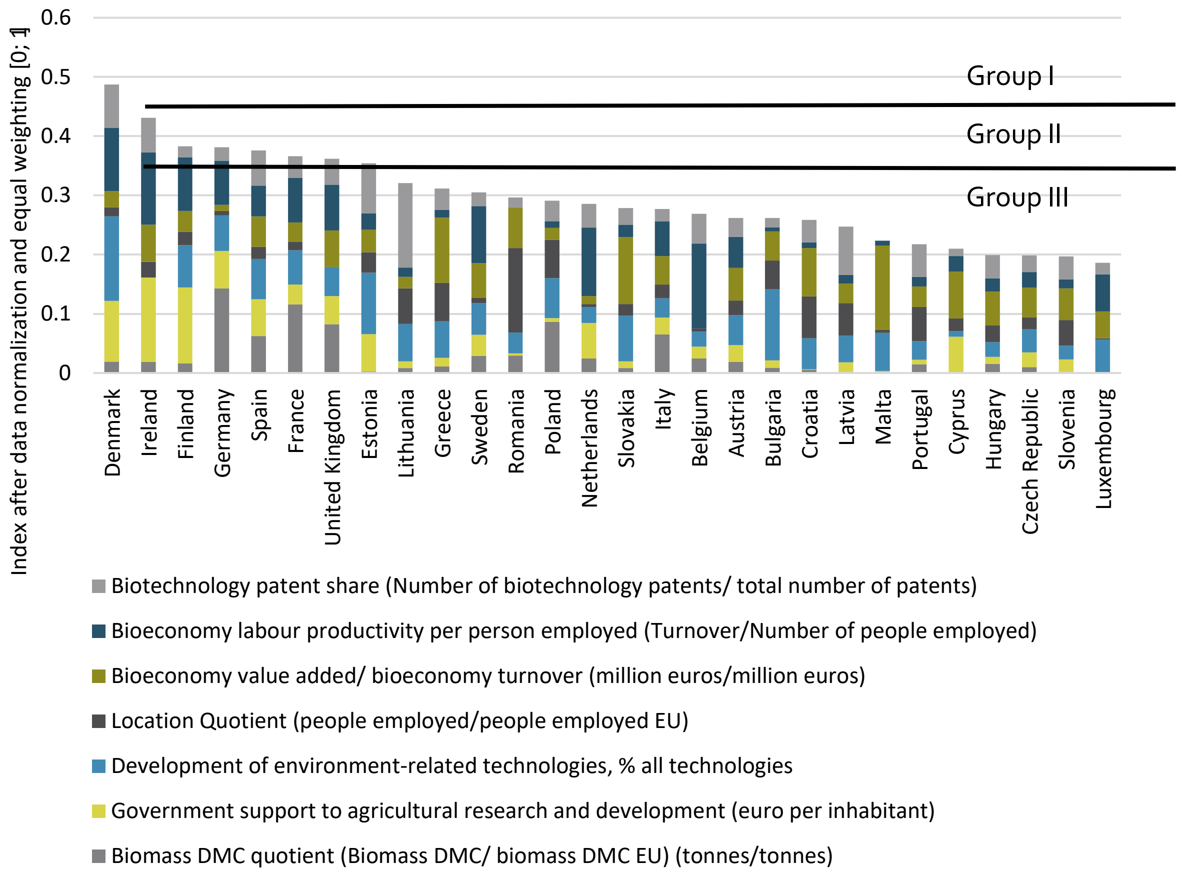

Fig. 2.9. Bioeconomy efficiency index for EU (2011–2015) (author analysis)
Databases: DataM, OECD and Eurostat.

Average values from used in timeframe of 2011–2015, see Figure 2.9. Number of indicators used are seven and data sources were from portal of agro-economic modelling – DataM, OECD, and Eurostat.

From all assessed countries Denmark, Ireland and Finland have the highest bioeconomy efficiency index, while Czech Republic, Slovenia and Luxembourg have the lowest index scores. The index scores between the highest (0.49) and lowest ranked (0.19) countries differ by 0.30. We apply three benchmark levels for the bioeconomy efficiency index for the analysed countries with 0.29 and 0.39 as the benchmarks. Only Denmark and Ireland qualify for group I, there are 11 countries in group II and 15 countries in group III.

The index representation in Figure 2.9 also indicates which of the indicators have higher or lower impact on each country's overall bioeconomy efficiency evaluation. For example, for Denmark and Ireland a large share of their evaluation comes from the three highest positions – patent share, bioeconomy labour productivity, and government investments into R&D in agriculture sector. For Denmark another strong position constitutes environmental technology development. The share of government support for R&D in agriculture sector is the highest only for the top three countries. The highest impact from the indicators bioeconomy labour productivity on the overall score is for Belgium, followed by Ireland and the Netherlands.. This might be related to the fact, that each country has selected its specific pathway for bioeconomy development. This does not mean that any one country's strategy is awry, however the bioeconomy efficiency index allows the decision makers to identify the most influencing indicators for each country to focus on strengthening the country's performance and could help in bioeconomy strategy development.

2.2. Meso-Level: Innovation Transfer, Market and Economic Analysis

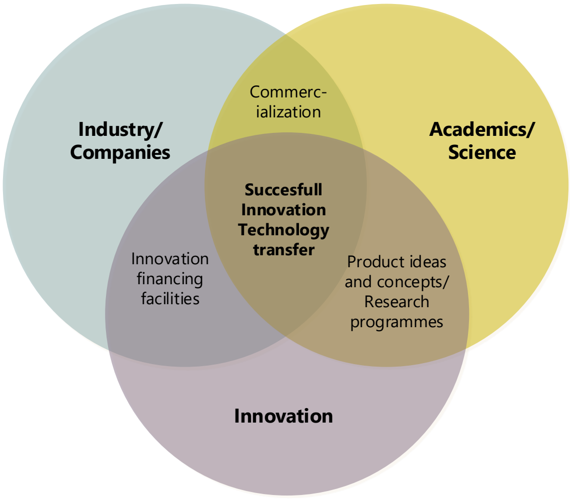

Fig. 2.10. Triple helix of knowledge drivers in bioeconomy through technology transfer.

Major commercialization gap is the knowledge gap between academics and industry [154], the challenge is to link the market needs to new research and to industries (Fig. 2.10). Energy and product consumption increases because of increasing population and welfare level, leading to unsustainable use of resources, resulting in an increase in the use of fossil resources for product production, which has a negative impact on climate and the environment. Insulation packaging industry is an energy intensive production process mainly depending on fossil resources that do not degrade in nature, causing additional load on the environment. Energy consumption and impact on environment can be decreased by implementing bio-based products with new technological solutions. The main issue for new bioproducts and technologies entering the market is inefficient commercialization strategy and high product costs that cannot compete with fossil-based products.

The analytical framework for assessing the potential innovation [47] for commercialization has been modified with a focus on feasibility assessment in the early development stages, although it is needed in all stages of technological readiness levels (TRL), shown in Figure 2.11. In the early development stage – from TRL3 to TRL5, the first feasibility study on eco-innovation should be conducted. In the basic technology stage (TRL1, TRL2), market analysis can be done, but there will not be sufficient data available for economic analysis at this stage.

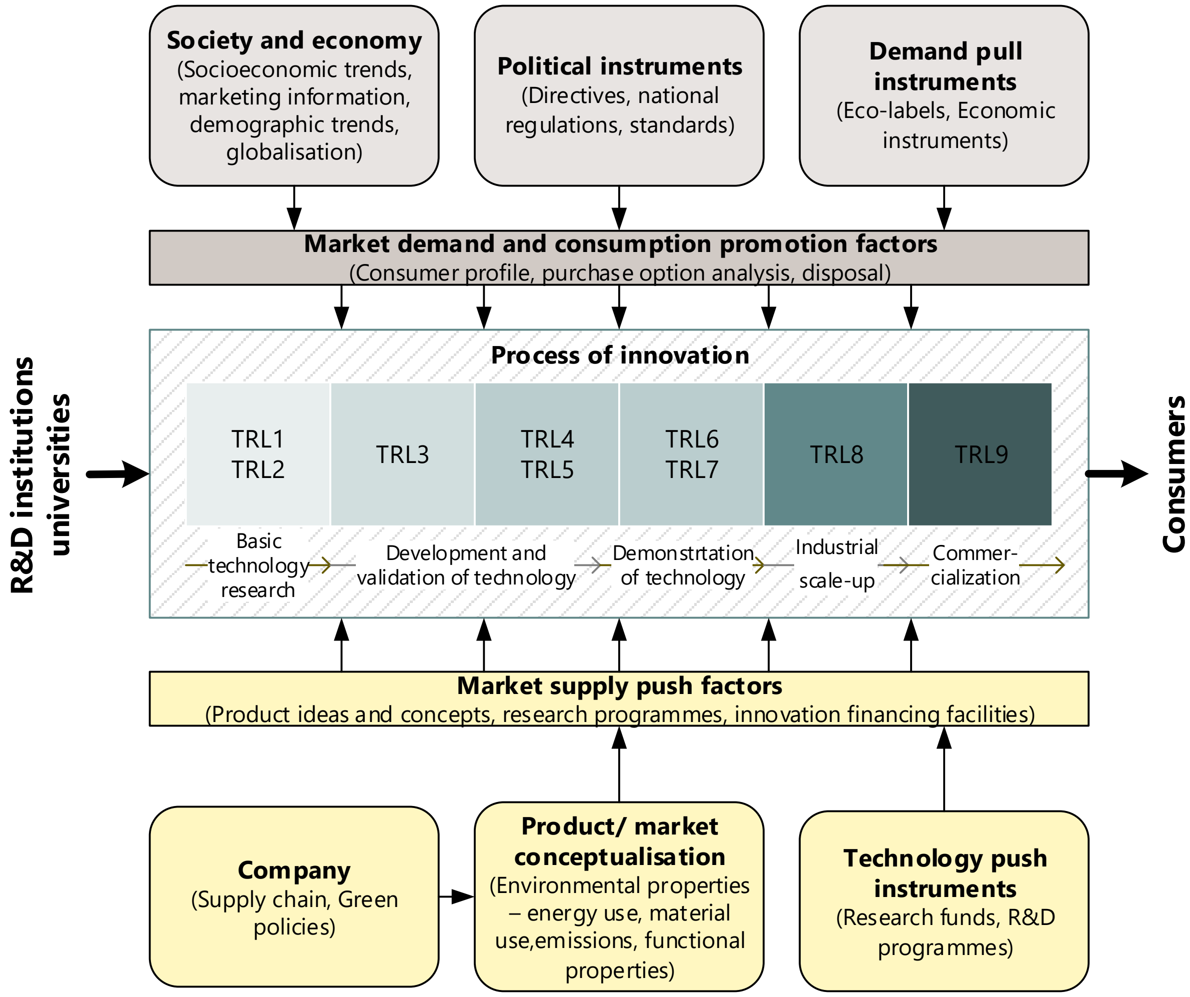

Fig. 2.11. Analytical framework for assessing the potential innovation for commercialization.

2.2.1. Bioeconomy Investments: Market Considerations

The introduction into the forestry sector of bioeconomy has led to the search for new high value-added bio-products that can be produced using the woody biomass residue from timber harvesting. Any introduction of new bio-products must be justifiable from economic, socio-economic, and technological points of view. For successful commercialization, one of the important consideration is the market potential for such products.

Case study of three products: lyocell (textile), bio-oil and xylitol

A case study has been developed for three existing products – lyocell (textile from wood), bio-oil and xylitol (a sweetener). After the results have been obtained, the capability of a product to enter a market as a primary product or as a value-added by-product of a biorefinery or not to enter at all should be determined.

In most situations at least 3 competitors have been evaluated. But in the case of bio-oil there are only 1 or 2, as shown in Table 2.1, because the evaluation is based on the direct use of bio-oil excluding the use of products that can be further obtained or derived from bio-oil. Competitors are chosen based on the product not the resource. Sorbitol and maltitol have been selected as competitors for xylitol, where both are low-intensity sweeteners, the same as xylitol.

Table 2.1

Total Weighted Scores for Competitive Advantages

	Total weighted score	
	Local market	Export market
Lyocell (all textile segment)	3.95	4.15
1. Cotton	2.65	2.85
2. Synthetic (PP)	3.10	2.95
3. Wool	2.45	2.75
Lyocell (natural segment)	4.30	4.30
1. Cotton	2.55	2.70
2. Linen	2.85	2.85
3. Wool	2.95	2.75
Bio-oil	4.00	4.20
1.Natural gas	3.15	3.20
2. Heavy fuel oil	–	1.30
Xylitol	–	4.35
1. Sorbitol	–	3.80
2. Maltitol	–	3.25

Table 2.1 shows the total weighted score for products and their competitors. In all textile segments the strongest competitor is considered to be the synthetic. In the natural segment (the segment that includes only natural fibres), wool is the strongest competitor in the local market and linen the strongest in the export market. The strongest competitor for bio-oil is natural gas. For xylitol, it is sorbitol.

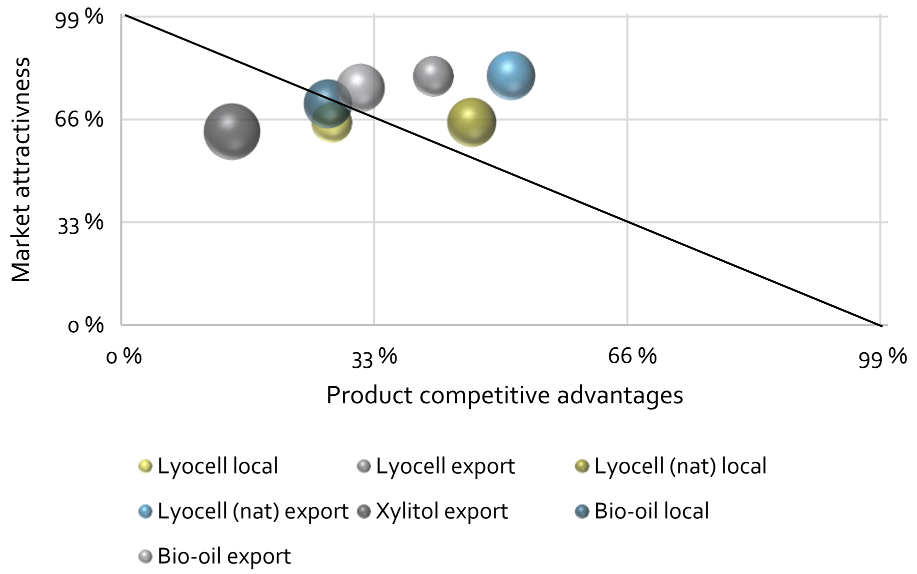

Fig. 2.12. Results of GE–McKinsey matrix.

Results (Fig. 2.12) for lyocell are the following – lyocell local market attractiveness is 65 %; its competitive advantage 27 %; its export market attractiveness is 80 % and competitive advantage 41 %. Lyocell shows better results than the competition in the natural segment –

lyocell local market attractiveness in the natural segment is 65 %, and 46 % for competitive advantage; lyocell natural segment export market attractiveness is 80 % and competitive advantage 51 %. The results for bio-oil show that its competitive advantage is low: 27 % for the local market and 31 % for the international market. In the local market, its attractiveness reaches 71 % and in the international market 76 %. As for xylitol, the strongest competitor is calculated to be sorbitol. The relative competitive advantages are only 14 % in international markets; while among low intensity sweeteners, its market attractiveness is 62 %.

2.3. Micro-Level: New Vision on Invasive Alien Plant Management System

The scientific literature already indicates the scientific potential for solving this problem, because the application of scientifically-based methods allows not only to find innovative and environmentally friendly technological solutions for the use of invasive plants in production, but also to determine the potential for commercialization and valorisation, the impact on the environment and the climate throughout the product life cycle, the availability of resources, and the opportunities for using alternative resources, which is very important in the case of invasive plants as a resource. Therefore, as a first step for the research towards increasing the value of invasive alien plant biomass, MCDA applied to categorize and prioritize various IAP species to further select those species for which an in-depth valorisation assessment should be done. The main concern about using IAS as potential biomass source is the risk of cultivating. There should be political instruments set to exclude this risk, therefore one of very important aspects for product production is to find a non-invasive plant substitute biomass, to ensure sustainable production.

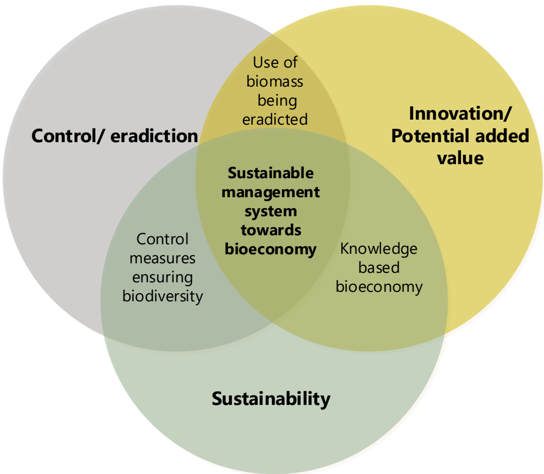

Fig. 2.13. The main pillars of the invasive alien plant (IAP) management system.

The main pillars of the invasive alien plant species management system can be seen in Figure 2.13. The use of invasive plants for production of products opens up opportunities not only for bio-economy development and acquiring the benefits related to it, but also creates a new stock of bioresources, without competing with agricultural crops intended for food production. At the same time, the product production should aim to find solutions that can later be applied for the use of other bioresources, thus reducing the risk of deliberate cultivation of invasive plants.

The proposed methodology (Fig. 2.14) is based on existing management plan, with an addition on new vision where after mechanical control, invasive plant species create potential biomass for product production, however, there should be clear assessment on biomass availability that would have economic viability, and there should also be an assessment on sustainability and possible substitution with other non-invasive plant biomass.

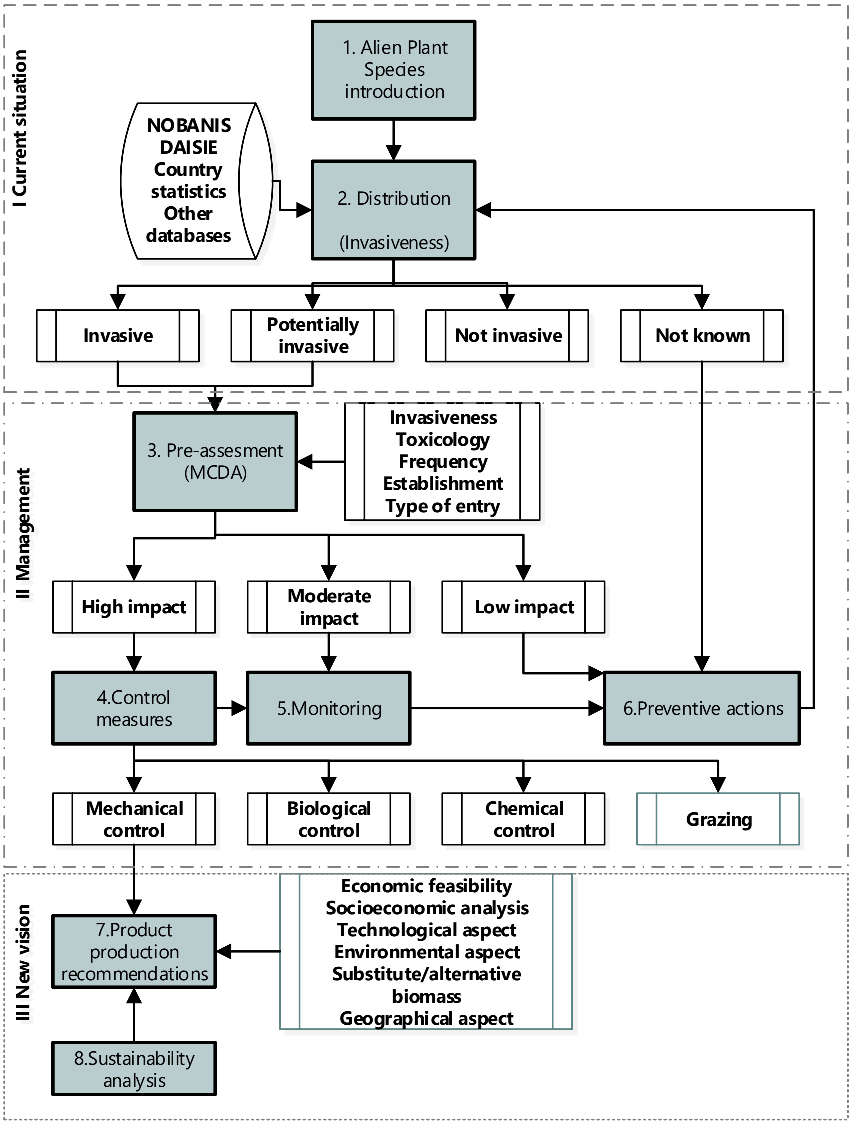

Fig. 2.14. New vision on invasive alien plant management system.

I Current situation is well researched at international and national level, there are several databases created that can be used on data selection: DAISIE (Delivering Alien Invasive Species Inventories for Europe) [187], NOBANIS (The European Network on Invasive Alien Species) [188], GISD (Global invasive species database) [189], CABI [190], MedPAN (network of Marine Protected Areas in the Mediterranean) [191], and SEBI-2010 [192], all can be found in EASIN species mapper [94], which offers Europe data on environment, impact, species status, taxonomy, and pathways. Based on current situation, one of the most important indicators is invasiveness, not all alien species are invasive, but for early detection and eradication the invasive and potentially invasive species must be selected.

II Management System for IAS management differs between countries, and there are national management plans developed in each of the countries, as well as at European level. There could be a potential multi criteria decision analysis (MCDA) in place, to create a common framework on invasive species selection at national level. There are several studies on indicators that should be selected, but a common framework would be an essential and possible way to use for every country as pre-assessment, where priority species can be selected for further analysis. Such criteria selection is still under development in Latvia. Control measures, monitoring and preventing actions are already in place.

MCDA method technique of order preference by similarity to the ideal solution (TOPSIS) was used to prioritize the invasive alien plant species occurring in Latvia according to their valorisation aspect. In this case the ideal solution is the species that show priority for further assessment of impact on ecosystem services, to biodiversity, social and economic impact (high, moderate or low). The alternatives are the invasive or potentially invasive alien plant species detected within a country.

III New Vision The new vision contributes at economic and social levels, assessment has already been described in previous studies [89], [194]–[196]. IAP as biomass for product production should be under legal permit to ensure that the production is under elimination practices of invasive plant species, and could be as a side stream of production with the same qualities provided from another biomass. In terms of bioeconomy there should be a higher added value product, but assessment is required and it could be a multi criteria decision analysis, as presented in previous studies. IAP as biomass source could be transferred from mechanical control, as it provides IAP as waste material.

Research results are presented by analysing the national level case of Latvia. First, the current situation in Latvia regarding invasive plant species is characterized from registered alien plant species to their invasiveness, distribution and establishment. Sankey diagram [197] has been chosen for flow visualization. In Latvia, of 636 alien plant species 210 are not invasive, and for 269 species there is a lack of information on invasive character, however as most of them are rarely distributed, there should not be serious concerns. Invasive and potentially invasive species should be more researched, as most of them have already been established. Criteria have to be selected and both invasive and potentially invasive species should be analysed.

Assessment of MCDA

After the preliminary analysis of alien species and their invasiveness, MCDA was made on invasive and potentially invasive species, altogether 157 species were analysed. The aim of MCDA analysis is to prioritize the invasive alien plant species occurring in Latvia according to their valorisation aspect.

MCDA TOPSIS results in Figure 2.15 show similarity in some ratios, meaning that there can be variation groups of species that share the same ratio.

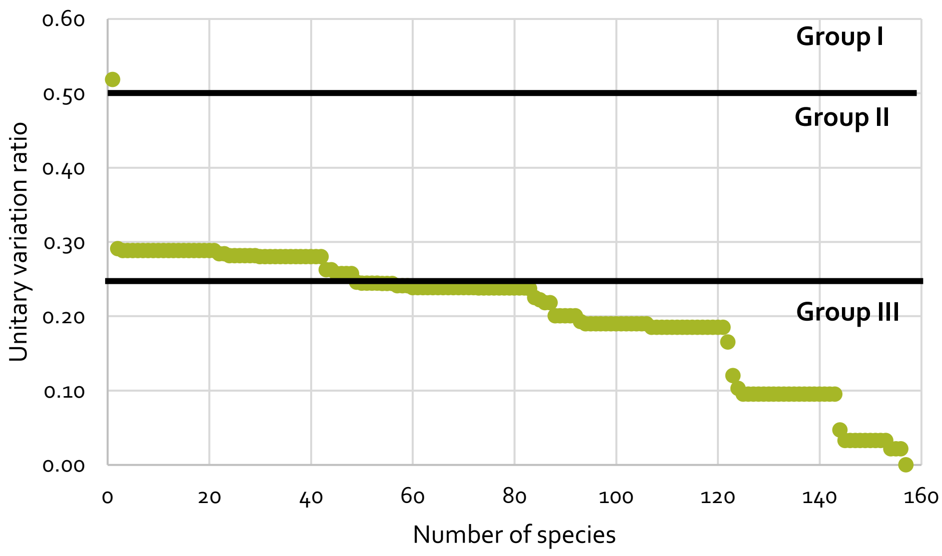

Fig. 2.15. MCDA-TOPSIS unitary variation ratios of analysed IAP.

Results are divided in three levels that could determine priority selection for further studies. In the first level, that has the highest score, is IAP species *Heracleum Sosnowskyi* M., in this case the most decisive criterion is toxicology, because the sap of this species is a threat to human health. There are 48 species in group II for which the evaluation score is higher than 0.25 and that could also be analysed for potential monitoring and risk assessment of the impact to biodiversity, and valorisation possibilities. Although most of the analysed species fall into group III, and therefore would not be nominated the highest priority, however, some species in group III are with score that is very close to the benchmark. So it could be advised to further study in detail about 80 species that show higher scores, especially because valuation score on some of the species that have ratio 0.244 was high, as they are established (score 3), invasive (score 2), very often distributed (score 4), and intentional and unintentional type of entry (score 1.5); such species is, for example, *Bellis perennis*. On the other hand, for a species that have a ratio of 0.281, valuation score was slightly lower, as they are established (score 3), invasive (score 2), often distributed (3), and intentional and unintentional type of entry (score 1.5), for example, *Solidago Canadensis*.

Suitable substitute bio-resources

One of the aspects that has to be considered is suitable substitute bio-resources in order to ensure product production by eliminating the risk of cultivating the invasive alien plants. Invasive alien plants are mostly comparable to lignocellulosic residues, and according to their composition, the corresponding products that can be possible to obtain are selected. Product preference strongly rely on biorefinery platforms, see Figure 2.16A.

Biorafinery platforms	
	Cellulose
	Oils
	Lignin
	C6 sugars
	C5&C6 sugars
	Hydrogen
	Proteins
	Pulp
	Fibre
	Biogas
	Electricity
	Pyrolytic liquids

A

Lignocellulosic biomass application	
	Animal feed
	Enzymes
	Biofuels
	Pulp&paper
	Fibre
	Fine chemicals
	Composites

B

Fig. 2.16. A) Biorefinery platforms; B) Lignocellulosic biomass (in this case – agricultural residues) application.

Final product production is based on lignocellulosic biomass applications (Fig. 2.16B), therefore suitable substitute bio-resource that does not require cultivation would be lignocellulosic biomass, as agricultural residues such as straw, stover, cobs, stalks, bagasse, etc. Lignocellulosic materials are one of the most abundant and naturally available bio-resource [203], continuous research shows the necessity to find the best solution for product production based on agricultural residues [204]–[206], it proves that available biomass substitute is freely available and secured and could convince stakeholders about long-term profitability of the technology.

MCDA TOPSIS analysis as pre-assessment should be tested on more than one country statistics, to prove the efficiency. Results of MCDA can be used as a pre-assessment at national level in order to set priority species to monitoring. The results show that the new vision on system confirms the existing system (the one species that has the highest score is already in regulation) and creates complimentary steps that could improve social, economic, and environmental benefits and give contribution to policy makers, invaded land owners, and municipalities.

Value of invasive species

The introduction of bioeconomy leads to search of new high added value bio products that can be obtained from local natural resources that have not been used or are used with low added value. One of which is invasive species. Tendency is to limit or to eliminate invasive species from environment therefore it can be labelled as waste. One of the bioeconomy principles is to turn waste into valuable products. European Union’s primary goal is to use bio resources for production of high value products [13].

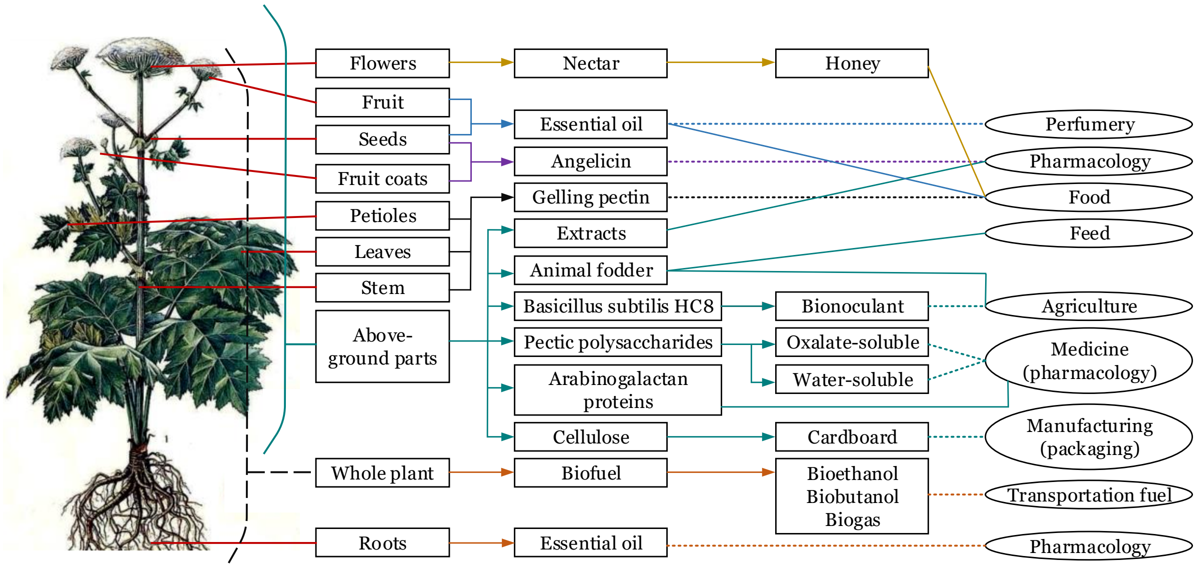

Fig. 2.17. Product classification according to the parts of the resource to be used.

All parts of *H. sosnowskyi* plant can be used to produce products. As shown in Figure 2.17, it is possible to obtain honey from flowers, which can be used in food industry [238]. It is possible to extract essential oils from fruits and seeds, which can be used in perfumery, in food and in pharmacy [239], [240]. From seeds and fruit shells it is possible to obtain furanocoumarin – an organic chemical compound derived from plants – angelicin, which can be used in pharmacy [241]. Pectin from the trunk, leaves and stalks can be used as thickener in food, for example, as gelatine [90]. From the surface of the plant a variety of extracts can be obtained, which in general, *Heracleum* L. genus has with the characteristics of antimicrobial, antipyretic, immune stimulant, analgesic and vasodilator properties and can be used for enzymes and psoriasis [242]. Silage may be prepared for fodder from the green mass, or be grazed fresh for cattle or sheep [243]. From hogweed it is possible to obtain a bioinoculant, which can be used in agriculture as a growth stimulator and biological control agent, for example, against tomato foot and root rot [244]. Studies are available on the production of polysaccharides from hogweed pectins [242], [245] and arabinogalactan proteins [246] that can be used in the food and pharmaceutical industry. The hogweed can be used for the production of cellulose, further for production of cardboard [247]. Biofuels can also be obtained from the whole plant. There are studies available on the production of bioethanol and biobutanol [248], [249], and biogas production [250]. Essential oils used in pharmacy can be obtained from roots and fruits [251].

2.3.1. Result of Experimental Analysis: Potential of Solid Biofuel

Evaluation has been done by experimentally determining biofuel parameters of two invasive plant species. In comparison to finding a new application, their use as solid biofuel pellets would not require additional investments for the construction of new production plant.

Sample preparation

Raw materials have been collected in Riga. *H. sosnowskyi* have been collected at the end of October (2017) and *S.canadensis* have been collected at the end of August (2017). Plant materials were initially pre-dried in the laboratory at ambient conditions and afterwards dried completely in a dryer for 18 hours at 105 °C. Afterwards samples were grinded in a mill (Vibrotehnik PM120) into particles smaller than 1 mm in diameter. To ensure that particle size is less than 1 mm, the mill contains a sieve with aperture size of 1 mm.

The binders were air dried for a week. The size of spent coffee grounds was already <1 mm. It has been checked using the sieve Retsch AS 400 sieve, with sieve aperture size of 1 mm. However, potato peel waste was ground in the mill.

The first eight samples were prepared as follows: pure *S.canadensis* (Sc), pure *H. sosnowskyi* (Hs), pure coffee grounds (CG), pure potato peel waste (PPW), and S with 6 wt. % CG, S with 6 wt. % PPW, H with 6 wt. % CG and H with 6 wt. % PPW.

All samples were prepared in accordance with the ISO (International Organisation for Standardisation) standard ISO 14780. The biofuel sample was pressed in a pellet press to produce a compact and dense test piece weighing 1.0 g ± 0.2 g.

The main biofuel characteristics were tested according to ISO standards on biofuel testing: ash content, moisture content, and calorific value.

After selecting samples for further analysis, new samples were made using the best material (higher calorific value shown for one of the species and increasing calorific value for binder) that contained 10 wt. %, 30 wt. % or 50 wt. % binder accordingly.

Outcome

The results of moisture content (wt. %), ash content (wt. %), and calorific value (MJ/kg^{-1}) have been determined during analysis. In order to be able to get reliable results of calorific value, it is necessary to determine and calculate chemical composition of each sample. All results are corrected with chemical composition values for carbon (C), hydrogen (H), nitrogen (N), and sulphur (S).

Table 2.2

Chemical Composition of Samples

	CG	PPW	S	H	S, PPW 6 wt. %	S, CG 6 wt. %	H, PPW 6 wt. %	H, CG 6 wt. %
C	52.95	43.90	44.80	46.52	44.75	45.29	46.36	46.91
H	6.76	7.20	6.46	5.79	6.50	6.48	5.87	5.84
N	2.10	0.80	0.37	0.59	0.40	0.47	0.60	0.68
S	0.12	0.10	0.20	0.00	0.19	0.19	0.01	0.01

Key: Sc, PPW 6 wt. % – *S.canadensis* (94 wt. %) mixed with 6 wt. % potato peel waste; Sc, CG 6 wt. % – *S.canadensis* (94 wt. %) mixed with 6 wt. % coffee grounds; Hs, PPW 6 wt. % – *H. sosnowskyi* (94 wt. %) mixed with 6 wt. % potato peel waste; Hs, CG 6 wt. % – *H. sosnowskyi* (94 wt. %) mixed with 6 wt. % coffee grounds.

The chemical composition (C, H, N, S) of pure materials – coffee grounds (CG) [261], potato peel waste (PPW) [262], and *S.canadensis* (Sc) [232] were taken from the available literature, *H. sosnowskyi* (Hs) from experimental analysis by chromatograph, and mixed samples were calculated according to proportions mixed, see Table 2.2. Samples that were tested after selecting suitable material and binder were *H. sosnowskyi* and spent coffee grounds accordingly. The proportions are as follows: Hs 90 wt. % : CG 10 wt. %, Hs 70 wt. % : CG 30 wt. % and Hs 50 wt. % : CG 50 wt. % and were calculated accordingly. According to EN plus pellet quality requirements for wood pellet quality classes, the amount of N and S is very important for solid biofuel quality. The highest acceptable amount of N is 1.0 wt. % and of S is 0.05 wt. % [263]. If the aim is to compete or to achieve the qualities similar to wood, then no more than 30 wt. % CG binder can be added.

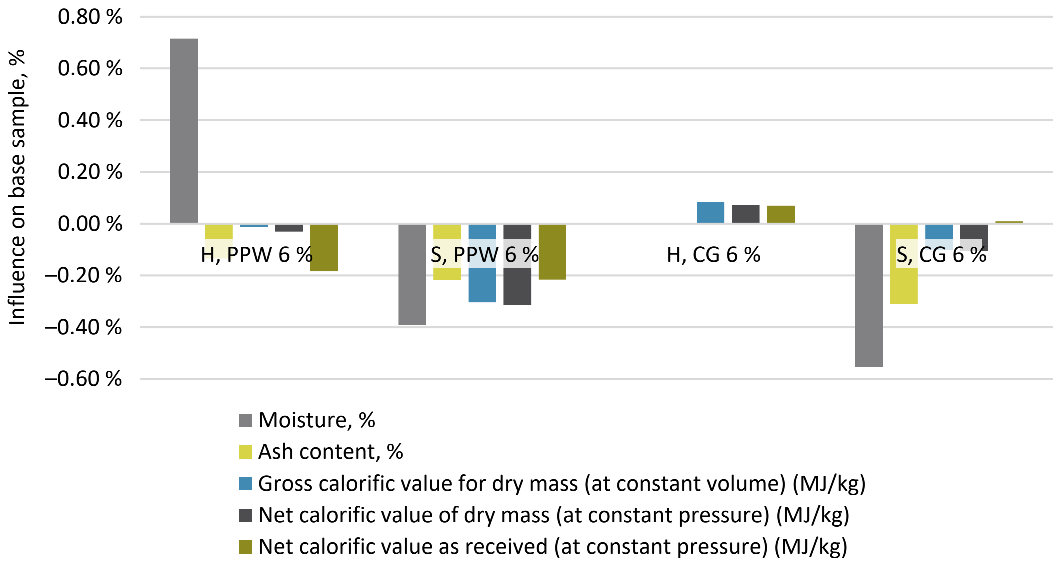

Fig. 2.18. Biofuel parameter changes by binder type.

In Figure 2.18 changes in biofuel parameters are shown regarding pure material sample (no binder added). *H. sosnowskyi* and PPW (H, PPW 6 wt. %) sample shows increase in moisture content, small decrease in ash content and calorific values. *S. canadensis* with both binders (PPW and CG) shows decrease in all parameters. Only *H. sosnowskyi* with CG binder shows increase in calorific value and no important changes in moisture and ash content. Therefore, *H. sosnowskyi* and CG were selected for further testing using different proportions of binder. There are no similarities between both binders and their effect on biomass parameters, for example PPW binder decreases moisture for one biomass, but increases it for the other. Therefore, further experiments with other types of biomass are preferable.

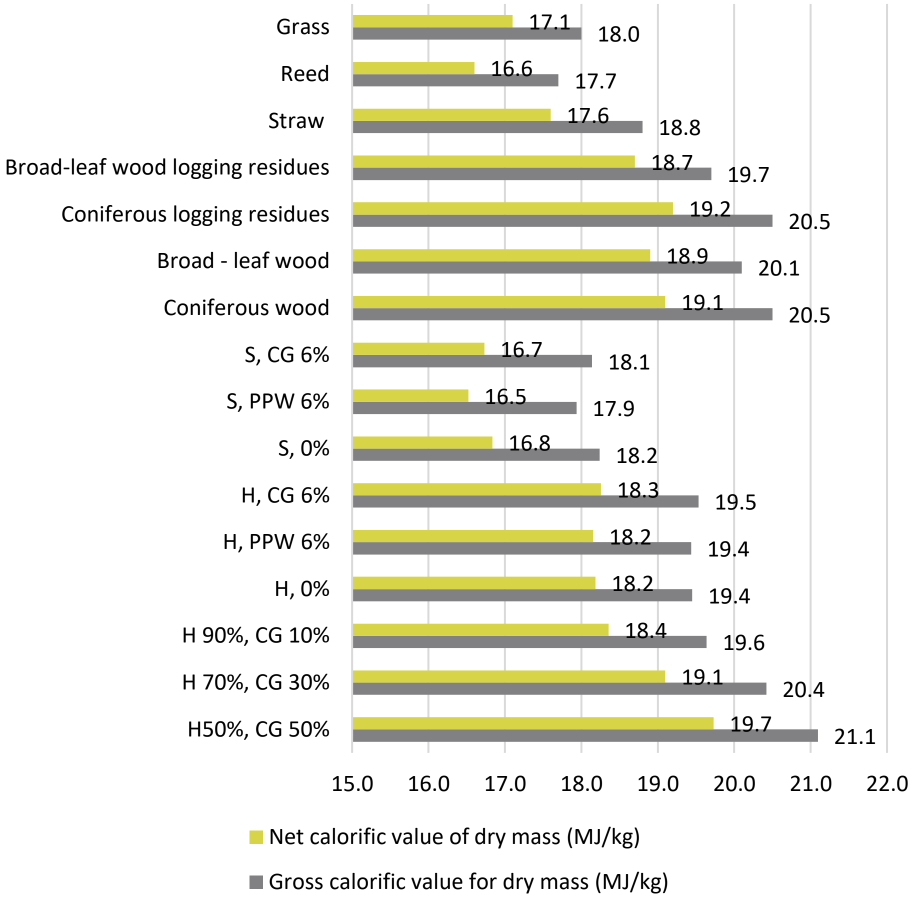

Fig. 2.19. A comparison of calorific values between existing solid biomass fuels and tested samples.

In order to determine the quality of the tested sample, a comparison with other existing solid biomass fuels was carried out. Typical values have been taken from ISO 17225-1:2014 standard. The main values taken for comparison are grass (in general), virgin reed canary grass (summer harvest), virgin straw materials from wheat, rye, barley, virgin wood logging residues for coniferous and for broad-leaf wood, and virgin wood materials for broad-leaf wood and coniferous wood.

The results of all *Solidago* samples, see Figure 2.19, correspond to reed and grass calorific values with and without binders, however *Heracleum* is competitive with broad-leaf logging residues. Moreover, mixed samples are even comparable with coniferous logging residues, broad-leaf wood and coniferous wood. The best results are for *Heracleum* sample with 50 wt. % coffee grounds. To determine the optimal proportion, ash content should be taken into account.

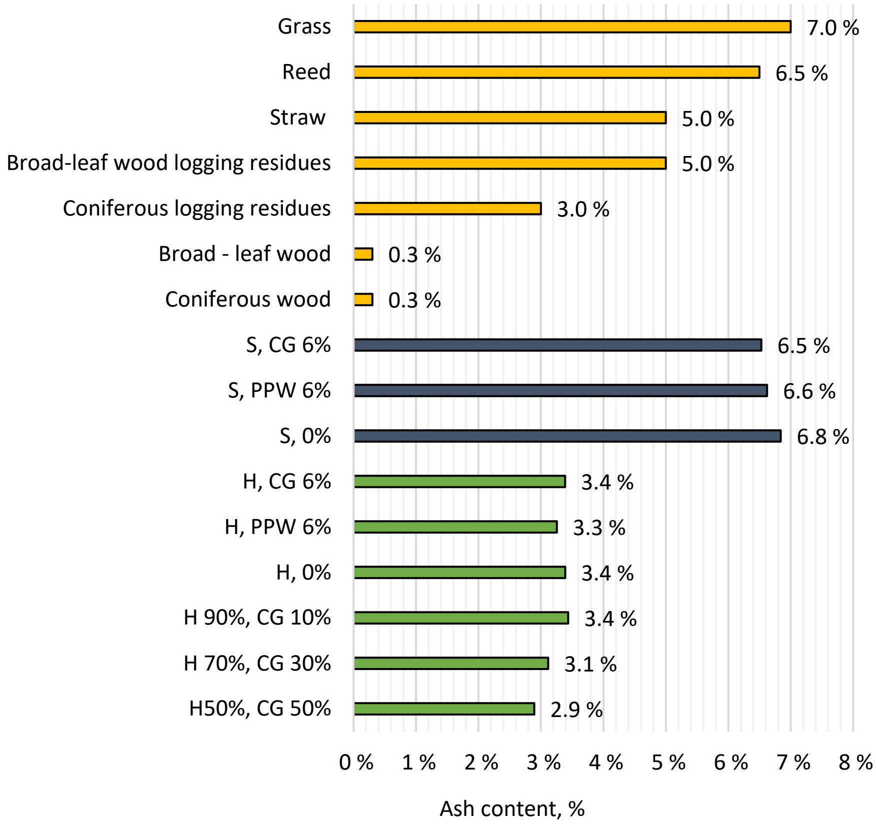

Fig. 2.20. A comparison of ash content in existing solid biomass fuels and tested samples.

Figure 2.20 shows ash content values of existing solid biomass fuels and tested samples. Typical values of existing solid biomass fuels are taken from ISO 17225-1:2014 standard. The lowest ash content is for virgin wood material (broad-leaf and coniferous). Non-woody materials cannot compete with virgin wood materials. However, average ash content of logging residues is 3 wt. % to 5 wt. %, which is similar to ash content of *Heracleum*. Ash content of *Solidago* mixed samples is similar to virgin reed canary grass, but results of pure *Solidago* is similar to grass (in general).

The methodology can be improved by adding more biofuel-characteristic parameters into the selection and is effective in comparison with other solid biofuels. The optimum coffee ground binder percentage is no more than 30 %, as the moisture content increases significantly. The increasing moisture content in higher proportions with coffee grounds could be reduced by means of oven drying.

Overall, the experimental analysis turned out better for *H. sosnowskyi* pellets with a coffee ground binder. The calorific value and ash content can be competitive against wood. Therefore, it is possible to use this bioresource as an effective energy source. From those conclusions it can be seen that the use of *H. sosnowskyi* with a coffee ground binder has been fully validated, and it is advisable to use it in industrial pellet production plants. However, from the energy balance and economic point of view, it is preferable to conduct further analysis. Further investigation for durability and bulk density for industrial pellets is clearly needed.

CONCLUSIONS

1. From the main multi–level methodology the conclusion is that bioeconomy should be assessed from bottom-up approach using micro- and meso-level assessment including transdisciplinary approach by working together with society (stakeholders), but top-down approach can help to determine the path for country level assessment in order to find drawbacks for bioresource transition towards sustainable bioeconomy, but top-down approach can help to determine the right path for country level assessment in order to find drawbacks – e.g. what necessary data should be collected in order to evaluate bioeconomy at international level.
2. The bioeconomy efficiency index allows to compare the level of bioeconomy development at international level. In this analysis no specific trend was distinguished between the bioeconomy development pathways in the EU 28 countries, but the overall evaluation indicates that the two highest ranked countries are Denmark and Ireland, mostly due to high investments in agriculture R&D and high labour productivity in bioeconomy. Bioeconomy efficiency index allows the decision makers to identify the most influencing indicators for each country to focus on strengthening the countries performance and could help in bioeconomy strategy development.
3. The main drawback of bioeconomy macro-level assessment is insufficient data, several good databases have been created for bioeconomy datasets, unfortunately the data is only till year 2015–2016, therefore the situation is the bioeconomy main growth years cannot be assessed because of lack of data.
4. The advantages of composite index include describing the multi-dimensional nature of the investigated phenomenon with a one-dimensional proxy that can be easily interpreted. In addition, composite indexes are easier to interpret than scoreboards of indicators; they can be used to follow the development of the phenomenon in time, they can include more information when there are limitations of size. The drawbacks, however, include potential misuse due to faulty interpretation.
5. With the developed meso-level framework it is possible to get an insight for innovation development potential for commercialization. Market factors clearly illustrate the situation even in early development stages and economic assessment is the first validation of innovation feasibility. These steps are advised to be repeated in next development stages when the technological readiness level is higher and there can be more precise evaluation. Also, it is important to repeat the economic and market assessment to see which stage in production process has the highest cost, and to reduce this stage or change the raw material within innovation development. The framework is successfully validated by the case of thermal packaging material and there is a clear vision which processes should be improved in next development stages.
6. Multicriteria analysis provides the ability to search for the use of invasive species to address the acute problems of agricultural land use. From invasive plants it is possible to produce a variety of products significant for national economy. Use of invasive species in products would create both economic and environmental benefits, but there

should be certification scheme developed to exclude the possibilities from deliberate cultivation of the plants and non-invasive plant substitute that ensures long term product production.

7. The application of multicriteria methodology allows to find the priorities of use of *Heracleum sosnowskyi* as bioresource for the production of bioproducts with high added value. Based on the results of the multicriteria analysis, three pharmaceutical products have the best potential: polysaccharides, angelicin, and essential oil.
8. Countries with forest resources should focus on adding value to pulpwood and forest residues, as one possibility to invest in textile industry for fibre production as there are higher potential not only for adding value for bioresources, but also biorefinery and energy production or innovations from forest residues like thermal packaging material. Future assessments should focus on robust analysis for biorefineries implementation and market values.
9. From experimental studies it is concluded that bioresource potential for invasive plant species as for solid biofuel potential are advised if characteristics are closer to wood than plant, as it is in case of *Heracleum sosnowskyi*, but not in *Solidago Canadensis* case. Future development should be focused on added value for product validations, such as fibre or chemical substances and biorefinery.
10. From experimental studies, analysing all parameters the optimal moisture content, ash content and calorific value is for *H. sosnowskyi* with 30 wt. % CG binder, from this experiment another residue potential rises, that is coffee ground use as effective pellet binder with high calorific value that could also solve coffee residue issue with potential for further research.

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