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Biotechonomy System Dynamics Modelling: Sustainability of Pellet Production

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Abstract**—**The paper discovers biotechonomy development analysis by use of system dynamics modelling. The research is connected with investigations of biomass application for production of bioproducts with higher added value. The most popular bioresource is wood, and therefore, the main question today is about future development and eco-design of products. The paper emphasizes and evaluates energy sector which is open for use of wood logs, wood chips, wood pellets and so on. The main aim for this research study was to build a framework to analyse development perspectives for wood pellet production. To reach the goal, a system dynamics model of energy wood supplies, processing, and consumption is built. Production capacity, energy consumption, changes in energy and technology efficiency, required labour source, prices of wood, energy and labour are taken into account. Validation and verification tests with available data and information have been carried out and indicate that the model constitutes the dynamic hypothesis. It is found that the more is invested into pellets production, the higher the specific profit per production unit compared to wood logs and wood chips. As a result, wood chips production is decreasing dramatically and is replaced by wood pellets. The limiting factor for pellet industry growth is availability of wood sources. This is governed by felling limit set by the government based on sustainable forestry principles.

Keywords**—**Bioenergy, biotechonomy, system dynamics modelling, wood pellets.

I. Introduction

IN the market of energy commodities, currently one of the fastest growing markets worldwide is pellet production and consumption [1]. Pellet production amount has grown from 1,7 million tons in year 2000 to 28 million tons in 2015 [2]. The major pellet consumer and producer is the market of Europe, followed by America and then rest of the world. Global net importer of wood pellets is European market, while the largest global net exporter is American market [3]. The European Union (EU) is responsible for 74% of the world's wood pellet consumption. Two main uses of wood pellet are heating and power production [4]. In 2014, Latvia was the third biggest pellet producer in Europe only behind Germany and Sweden [4]. All markets are expected to expand the pellet production, with the highest rise projected in the Southeast Asia countries, especially China [5].

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Market price is a key factor for the development of pellet manufacturing. Price of pellets recently has decreased considerably, and the fossil fuel price drop is an important factor for this decrease. It is necessary to decrease the price of pellets to make them competitive in the market; however, the pellet price increase is forecasted in the future [6].

The current situation in the pellet and woodchip export in Baltic Sea region countries indicates that Latvia stands out among other countries with the export of woodchips - a bioproduct with low added value. This means that resources, which could strengthen the development of state macroeconomic development, are flowing out of the country [7].

Aim of this research was to determine pellet development possibilities compared to the other energetic wood products as wood chips and firewood. System dynamics modelling method was used to carry out research.

II. Methodology

A. Method

System dynamics is a method to enhance learning in complex systems, often by using computer simulation models. System dynamics is a method to help us learn about dynamic complexity, understand the sources of policy resistance, and design more effective policies [8]. Powersim Studio 8 was used to develop a model.

Complex dynamic systems are affected by human behavior, which means that it requires not only technical tools to create mathematical models, but also knowledge about social and economic systems [8]. The structure and the dynamic behavior are interwoven, but also sequential, because there must be structure before there can be a system that can have a behavior [9].

System dynamics concept consists of three main elements, and it is possible to acquire adequate results when these elements are used correctly [10]:

- Stocks, flows, and feedback loops;
- Precisely set system boundaries;
- Causal relations not correlations.

Behavior is generated within the boundaries of the defined system. Only variables essential in creating a behavior of the system are included [9], [11]. Model consists of different feedback loops interacting with each other thereby producing the system behavior [9]. Basic structure is built by using stocks and flows [12]. First, the loop structure is formulated and only then main components are included [9].

The goal of system dynamic is to determine the possible dynamic development of the system; therefore, results must not be treated as a precise "point" prediction, but rather as a possible trend.

B. Dynamic Hypothesis

System dynamics modelling consists of multiple steps. At first the investigated problem is formulated. System dynamics models are always built to study a problematic behaviour, and only when the problem and goals are defined, it is possible to carry out the development of system dynamics model. After that follows the development of dynamic hypothesis during which the stocks and flows of the main model are being identified and defined, and it described how they could interact mutually. System dynamics modelling is based on the knowledge that the system structure influences its created behaviour, which means that, during the dynamic development, it is necessary to determine the mutual interaction of the elements and feedback loops between them.

To show the most important components of the system and their mutual interaction, the system causal loop diagram is being used. It helps to understand and characterise the behaviour of system.

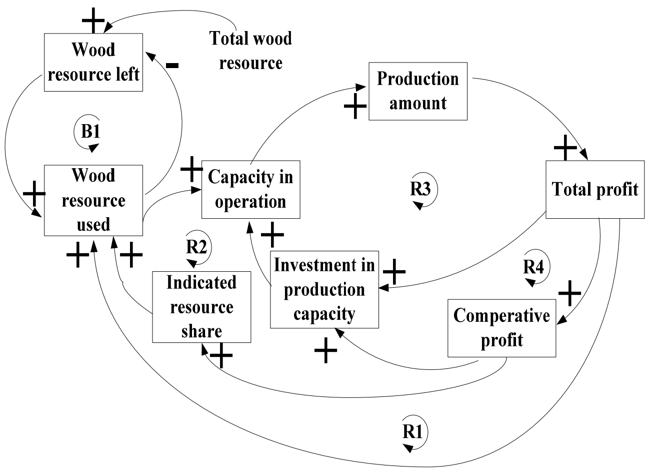

Fig. 1 Causal loop diagram

Causal loop diagram in Fig. 1 shows four reinforcing processes R1-R4 and one balancing process B1. The first reinforcing loop R1 shows that the more forest resources are used for manufacturing the particular product (firewood, woodchips or pellets), the larger manufacturing power must be installed, which further promotes even larger manufacturing volumes. With the increase of manufactured products, the profit from product sales also increases, which means that the relative profit in comparison with the other products also is larger, but that, on the contrary, will mean that the usage of forest resources for the manufacturing of the particular product will be increased even more.

The second reinforcing loop R2 is similar to R1, where larger amount of resources means larger installed capacity, larger amount of manufactured products, and larger total profit. Larger profit means additional resources, which can be dedicated for the research to improve the efficiency of processes and technologies, thus also increasing the amount of relative profit due to decreased usage of raw materials. The research process takes time; therefore, the increase of relative profit will not be instant, but there will be a delay. Increase of relative profit means that even larger part of total resources will be used for manufacturing the particular product, therefore also increasing the amount of resources allocated to the manufacturing process. This process also occurs with delay because time is required to compare the profits and make decisions in favour of increasing the share of the resources.

Third reinforcing loop R3 works beginning from the installed capacities. The larger is the installed capacity, the more products will be manufactured, which means bigger profit. If the relative profit is bigger than for the other products, that means the part of the profit can be redirected for building new capacities. Nevertheless, in case where the relative profit is smaller than the other profits, then the profit will not be redirected for building new capacities because the resources will be used for the manufacturing of the other products, and the current capacities will be underloaded. Delay is present between allocating investments for building new capacities and the currently operating capacities, while time is needed after making decisions to carry out purchase and installation of capacities.

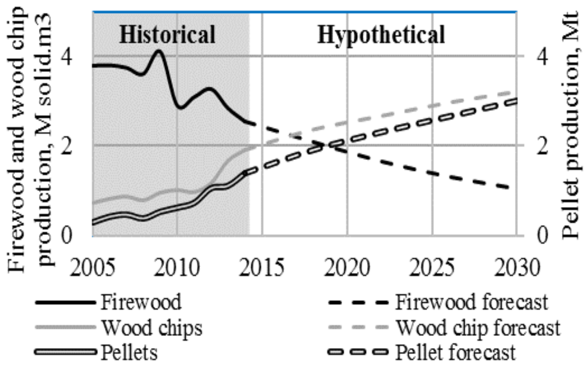

Fig. 2 Hypothetical energetic wood development forecast

The fourth reinforcing loop R4 works similarly to R3, but in this case, like in the R2 case, a part of the profit is allocated for research, promoting the increase of relative profit, therefore increasing the competitiveness with other products, which allows to invest part of the profit in installing new capacities. Nevertheless, the balancing loop B1 delays the infinite growth of forest usage resources. Because the total amount of forest resources used in energy industry is limited, it means that the more resources are used, for example, in the manufacturing of the woodchips, the more resources will be left for firewood and pellets. Amount of resources used for the manufacturing of one product cannot exceed the total available amount of resources because if the manufacturing of one product is more profitable than the others, then the product manufacturing volume will increase in S-type curve. Initially, the reinforcing loops will promote rapid increase of product manufacturing, but towards the limit of available resource, the effect of the balancing loop will increase, and the increased speed of manufacturing will decrease.

On the basis of historical data [7], [13], a forecast was stated that the usage of firewood would significantly decrease until 2030, which would promote the growth of woodchip and pellet manufacturing. Historical data show that, in the last 10 years, we can already observe significant increase in the woodchip and pellet manufacturing rate, while the firewood manufacturing amounts (excluding the year 2009 when rapid increase was experienced) are already decreasing rapidly. The decrease in firewood manufacturing and increase in woodchip manufacturing can be explained by the growing demand for woodchips in CHP plants. Woodchip manufacturing from logging residues are developing as well. The decrease of firewood is also related to the increase of pellet manufacturing. The firewood manufacturing volume given in statistics databases is mainly shown together with the amount of firewood, which is later used in the manufacturing of pellets and woodchips. To easier understand how exactly the distribution of fuelwood changes in the sections, the volume of firewood shown in Fig. 2 is already given as the volume provided for the final consumption, and the amount provided for the manufacturing of pellets and woodchips is not included in this figure. The data of Central Statistics Bureau is additionally converted, taking into account the Forest and Wood Products Research and Development Institute (MEKA) calculation method for the household firewood consumption. Data for woodchip and pellet manufacturing are shown by using the similar principle.

C. Model Structure

Model structure is built based on principles explained in the previous section. Stocks and flows are defined based on the actual situation in Latvia, distributing total harvested wood between wood processing sectors. Wood is mainly used for production of veneer boards, particle boards, packing boards, sawlogs, and also for production of wood chips and pellets. Part of the wood is harvested as paperlogs which are later exported. Export and import rates of all wood resources are also taken into account. Stocks can be described with an equation [1]:

$$Stock\,(t) = \int_{t_0}^{t} [Inflow\,(s) - Outflow\,(s)]ds + Stock\,(t_0) \quad (1)$$

Inflow(s) describes one or more incoming flows that go into stock at any given time s between initial time t_0 and current time t. Same is valid for outflows. In this case, if stock is total amount of felled trees, then inflow would be harvesting rate or felling rate which is regulated by the Forest Law [14] and related Cabinet of Ministers Order [15], but outflows would be different wood processing sectors. Initial values are taken from statistics [7], [13]. Our research scope was energetic wood from which firewood, wood chips, and pellets are produced, so we assumed that the other wood processing sectors will continue to produce at the current level and will not interact with energetic wood sector; therefore, they were not examined in more detail, with only exception being shavings and wood chips as waste from production processes which can be used in pellet production.

It is assumed that economic reasons are the main catalyst for a development of different types of energetic wood products. Another stock and flow structure is built for incomes and expenditures to realistically compare pellets, firewood, and wood chips, and total profit was calculated. It is vital to explain that model consists of not only stocks and flows, but also of the other variables which impact the behaviour of flows and which could be also impacted by the other flows and stocks. All mutual connections and feedback loops are determined and formulated with respective equations. For example, expenditure flow consists of different variables as technology capital costs, labour, energy, and the other costs. Costs differ depending on the product that we are looking at. For example, for a firewood production, felling costs are taken into account, while for the wood chip production chipping costs are used.

Additional stock and flow structures with respective variables and interconnecting links were also made for technology capacities, capital costs, power, heating, and labour as well as for projected development in technologies, which describes energy efficiency level. Reference [12] gives more detailed description about model structure as it was used as a base structure for development of model used in this research.

As stated before, wood chip, firewood, and pellet development were based on economic reasons by comparing their specific profits in Euro earned per every solid m^3 of wood used for production. Logit function was used to compare all of the products and to determine the share for each of them [12]:

$$\text{Share}_1 = \frac{\exp(\alpha \cdot P_1)}{(\exp(\alpha \cdot P_1) + \exp(\alpha \cdot P_2) + \exp(\alpha \cdot P_3))} \quad (2)$$

Symbol α is the coefficient describing the rate at which one product replaces the other, and P is the profit of the respective product.

III. Results

On the basis of historical data, the hypothetical fuelwood development scenario was established (in methodology). When comparing the hypothetical scenario with the one generated by the model, it can be seen that firewood and woodchip development trends are similar, but in the case of pellets, the hypothetical and model scenario differs substantially. All the values are recalculated to firewood solid cubic meters to compare more clearly all the product development trends. According to historical data, the hypothetical scenario anticipated that woodchips should develop similarly to pellets, only with slightly smaller increase rate. The result generated by the model in Fig. 3 indicates that the woodchip production amount could increase similarly to the one anticipated in the hypothetical scenario, but the pellet production development will not likely be as rapid as in the hypothetical scenario. It can be explained with the fact that pellet manufacturing in Latvia and in whole world has started to develop very recently, and the rapid rate of development has allowed to list Latvia in the leading world manufacturers of pellets, but in the case of limited resources, such rapid development rate cannot be infinite. Fig. 3 indicates that, already now, the pellet manufacturing takes up major part of fuelwood resources, and to increase the pellet manufacturing volumes as in the hypothetical scenario rate, it would be necessary to nearly completely decrease the usage of firewood and woodchip manufacturing as final products, to start to use more actively the paperlogs for pellet manufacturing, or to increase the timber felling volumes in the country.

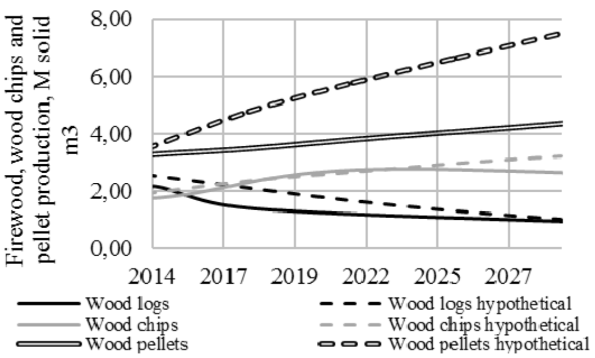

Fig. 3 Firewood, wood chip and pellet manufacturing

To understand, how the result generated by the model is composed, we must pay attention to the profit part. Because the resource selection preference in the model is done according to the profit indicators (Fig. 4), which is characteristic to the normal entrepreneurship, it is a very important ruling factor of fuelwood development trend. Manufactured volume of firewood and woodchips is given in cubic meters (bulk cubic meters for wood chips and solid cubic meters for firewood), but for pellets, the characteristic measurement unit is tonnes. To be able to mutually compare the profit indictors, they were related to the amount of timber used in production manufacturing, acquiring in the result the specific profit indicators. All values were expressed in solid cubic meters.

As can be seen in Fig. 4, the profit from pellets substantially exceeds the profit from firewood and wood chips, and this difference will increase even more as the pellet manufacturing develops. Explanation for this could be seen in the causal loop diagram (Fig. 1). Reinforcing loops in the case of larger profit also promote the increase of specific profit, thus promoting even larger difference between the value of pellet specific profit and the value of firewood and woodchip specific profit value. Disparity of profit values indicates that the pellet manufacturing increase can potentially be even larger, but in this case, we must take into account the circumstances that prevent this from happening. As we can see in the firewood case (Fig. 3), its manufacturing volume could decrease by approximately 50%, but we must take into account that this decrease is mostly happening due to the amount of wood acquired in licensed felling sites. Parts of the firewood resources are acquired in private forests without license. Legislation specifies cases when it is possible to carry out logging in private forests without acquiring permit [14], and the studies show that in average in one private forest 10 cubic meters of wood are logged in such way [7]. Because these are comparatively small amounts, and their collection and transportation from individual households and private forests could be unprofitable, it can be assumed that this part of wood will most likely be used in local households as firewood. This means that this part of firewood does not compete with pellet manufacturing; therefore, a more rapid decrease in firewood manufacturing most likely will not occur.

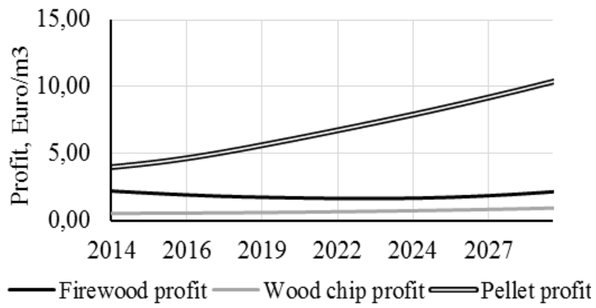

Fig. 4 Fuelwood product profit

The woodchip development rate acquired from the model is close to the one determined in the hypothetical scenario. Woodchip manufacturing increase is forecasted. It must be taken into account that there are two types of woodchips; industrial woodchips (from chipping the firewood, also a part comes from manufacturing process surplus) and forest woodchips (manufactured from logging surplus – stumps, branches and treetops). Industrial woodchips can be used in the pellet manufacturing; therefore, they compete with pellet manufacturers, but the forest woodchips can be used only for energy needs. Model results indicate that the total woodchip amount could increase, but we must note that, when comparing the profit of woodchips and pellets, it can be seen that pellet manufacturing is larger; therefore, the manufacturing amount of industrial woodchips as a final product will most likely decrease at the expense of pellet manufacturing increase, but the total amount of woodchips could increase exactly due to the increase of forest woodchip manufacturing. In the recent years, the forest woodchip usage volume has started to increase considerably.

In general, the results indicate that the pellet manufacturing development is a very plausible scenario, and taking into account the rapidly rising demand in Europe for pellets, a very large export potential exists. However, to be able to increase the pellet export volumes, it is necessary to increase the acquisition volumes of energetic wood, because the results acquired in the model indicate the ratio structure of the energetic wood necessary in the domestic market, and it is anticipated that, in Latvia, not only the amount of produced pellets will increase, but also the consumption, substituting the firewood and woodchips.

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