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Modelling the Development of Above-Ground Biomass Energy Reserves of Four Economically Important Coniferous Woody Species

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Abstract: The goal of renewable energy is to replace energy production from fossil fuels. In that sense, forest biomass is essential renewables. This article presents the results of the development of energy reserves in fractions, increments and the total above-ground biomass of coniferous stands (spruce, fir, pine, larch) during their economic cycle. The experimental material comes from 22 forest stands located mainly in Central Slovakia, to a lesser extent also in Western and Eastern Slovakia. Energy reserves of coniferous stands were calculated based on the volume production of above-ground biomass fractions taken from mathematical models of yield tables and average values of their basic density and calorific value were determined. The research showed that as the age of the stands increased, the share of energy in the wood fraction increased, while it decreased in the bark fraction, and especially the branch fraction. The curves constructed in relation to the age of the stand and site index have a very similar shape to the curves of the total current annual energy increment of coniferous stands. The energy reserves of stands grew faster at the age of 40 to 80 years than at the age of 80 to 140 years. Spruce had the highest total mean energy increment, followed by fir, larch and pine. As the age of the stands increases, the energy reserves of the increments slightly decrease and the efficiency of solar energy significantly decreases. It peaks practically at the age of reaching the maximum annual energy increment.

Keywords: coniferous stands; development of energy stocks; solar energy use efficiency; forest models

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1. Introduction

Forests are vital for livelihoods of human populations, providing a multitude of goods and services. Such socio-ecological complexity has been translated into different modelling approaches to try to understand forest systems. Forest models have been developed at all kinds of complexity levels, from very complex, integrative models to simpler models focused on one specific eco-physiological process [1].

Models potentially integrate a wide range of system knowledge and present scenarios of variables important for any management decision. Based on historical analyses, Pretzsch et al. [2] identified five forest management paradigms: (1) multiple uses, (2) dominant use, (3) environmentally sensitive multiple uses, (4) full ecosystem approach and (5) eco-regional perspective. According to the mentioned authors, the use of a set of models with a different focus that can be selected from a kind of toolbox according to particular needs is more promising than developing one overarching model, covering ecological, production and landscape issues equally well.

Although growth and yield tables have been used in forest science for more than 200 years, the model JABOWA by Botkin et al. [3] is usually considered as the first modern model based on computational algorithms. Since then, algorithm-based forest models have kept evolving, creating an impressive "forest of models" by itself. Many of such models were created for specific applications, whereas others intended to be theoretical explanations of how forest ecosystems grow [1].

Among the different terrestrial ecosystems, forests are the most important biomass carbon producers, and consequently, they are also the major source of biomass for energy [4]. Larcher [4] states that trees are richer in energy than herbs and that, in general, the energy content depends directly on the carbon content of the substance. Out of the plant substances, terpenes have the highest energy content of 46.9 kJ g^{-1}, followed by lipids with 38.9 kJ g^{-1} and lignin with 26.4 kJ g^{-1}. Larcher [5] hypothesized that in many cases, lower calorific values can be an evolutionary advantage as less energy needs to be invested.

Zeng et al. [6] stated that the calorific value of plants is an important parameter for evaluating and indexing material cycles and energy conversion in forest ecosystems. The distribution of plant biomass can also be greatly influenced by climate change and habitat fragmentation, which bring about severe threats to biodiversity [7,8]. At the same time, the global demand for energy is an increasing pressure on natural resources, including forests [9]. The use of energy from biomass is growing rapidly, mainly due to the need to reduce greenhouse gas emissions [10]. Abbasi and Abbasi [11] also point to the renewed interest in energy from biomass, which is perceived as a carbon-neutral source of energy, in contrast to carbon-producing fossil fuels, whose widespread use has led to global warming and acidification of the oceans. In addition, biogas production is part of the EU's policy to reduce dependence on fossil fuels and use energy from renewable sources [12]. Biomass fuels are namely considered to be renewable and do not affect the overall CO_2 balance in the atmosphere [13]. However, this only applies on the assumption that there will be no significant change in the average species composition, density, age and area of plant communities, especially forest ones.

In current forestry, the volume production of tree biomass is usually expressed in the form of yield tables simulating volume production depending on the age of the stand and the quality of the site. Yield tables used in Slovakia simulate the volume of above-ground biomass of woody plants and also of their main parts (wood, bark, branches with bark) and increments [14]. For this reason, they can be used effectively to convert the volume of biomass to dry weight and subsequently to the energy stock of forest stands.

In addition to the amount of energy stored in biomass, it is also useful to know the ability of woody plants to use global solar radiation. Current photosynthesis is the basis of all food and fibre production, and biomass-based biofuels are a source of renewable fuels. However, between 98 and 99 percent of solar energy reaching Earth is reflected from leaves and other surfaces and absorbed by other molecules, which convert it to heat. Thus, only 1 to 2 percent is available to be captured by plants [15]. Zhu et al. [16] state that the proportion of total solar energy within the photosynthetically active band (400–740 nm) is 48.7%. This means that 51.3% of the incident solar energy is not available for the photosynthesis of higher plants. The maximum conversion efficiency of solar energy to biomass is 4.6% for C3 photosynthesis at 30 °C and today's 380 ppm atmospheric [CO_2], but 6% for C4 photosynthesis. This advantage over C3 will disappear as atmospheric [CO_2] nears 700 ppm [16].

Layton [17] states that solar radiation has an energy density of 1.5 microjoules per cubic meter (1.5×10^{-6} J m^{-3}). The coefficient of utilization of solar radiation as an amount of formed biomass does not only depend on climatic conditions, but also on the photosynthetic ability of plants, the arrangement of leaves in crowns and the inclination of leaves with respect to incident radiation. These relationships have been studied in detail for instance in Japan [18], the Netherlands [19], Estonia [20] and Czechoslovakia [21].

Larcher [5] expresses the energy efficiency of solar energy accumulation in the forest stand as the ratio of the energy accumulated in the above-ground biomass of the trees and solar energy, which falls on the earth's surface at the same time. The author states that the upper limit of solar energy converted into forest biomass is 2%, while in the case of most woody plants it is less than 1%. For forest stands in Germany, Pretzsch [22] used an average annual global radiation of 36,000 GJ ha^{-1}. For the net wood production of spruce, beech, pine and oak, he calculated the coefficients of efficient use of solar energy in the range of 0.005–0.009. This means that only 0.5%–0.9% of the annual solar radiation is used for wood production.

Duvigneaud [23] states that in the temperate climate zone, 1 hectare of common forest produces (in dry mass) about 8 tons of wood, 3 tons of leaves, 1 ton of fruits and 1 ton of roots per year. Combustion of this phytomass will release energy of 245.7 GJ ha^{-1} (151.2 + 56.7 + 18.9 + 18.9). Thus, according to the above author, the efficiency of the net productivity of the common stand reaches about 0.6%, respectively, and 1.2% of photosynthetically active radiation.

The lack of multidimensional data is one of the main gaps that limit the knowledge and assessment possibilities of European forests. The aim of this work is, therefore, to find out and evaluate data on trends in the development of energy reserves in: (1) fractions of above ground biomass, (2) total average increments and total current annual increments, (3) total above ground biomass of coniferous forests, and (4) trends in the efficiency of the use of solar energy by coniferous forests of Slovakia depending on their age and site index. In this way, it is possible to fill the research gap and to obtain a picture of the energy reserves of coniferous stands calculated based on the volume production of above ground biomass fractions taken from mathematical models of yield tables and determined average values of their basic density and calorific value.

2. Materials and Methods

2.1. Characteristics of Forest Stands and Processing of Biomass Samples

Experimental material comes from 22 coniferous stands selected in the main growth areas of the investigated woody species, mainly in Central Slovakia, and to a lesser extent also in Western and Eastern Slovakia (Figure 1).

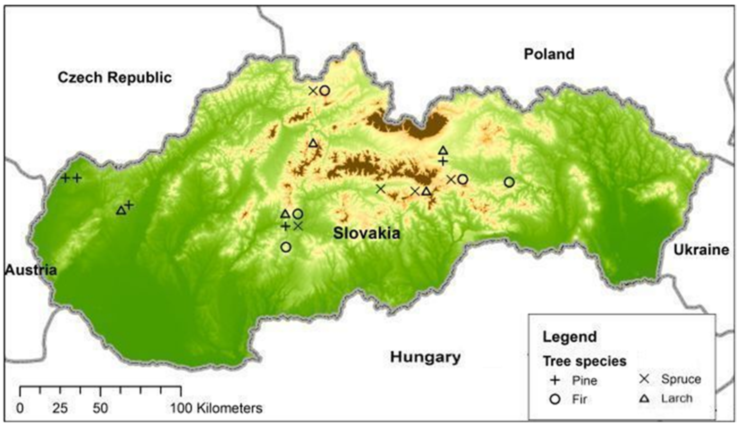

Figure 1. Location of examined coniferous stands [24].

The characteristics of the sampled trees and fully dense stands of Norway spruce (*Picea abies* (L.) H.Karst.), Silver fir (*Abies alba* Mill.), Scots pine (*Pinus sylvestris* L.) and European larch (*Larix decidua* Mill.) are in Table 1.

Table 1. Basic characteristics of the sampled trees and stands [24,25].

Tree Species	Sampled Trees	Dbh (cm)	h (m)	Age (Years)	Site Index	Altitude (m)
Spruce	12	20–62	23–38	35–105	26–42	435–1070
Fir	11	23–75	22–39	35–153	24–40	390–950
Pine	10	25–51	24–30	75–108	24–30	165–940
Larch	10	26–56	24–35	40–100	28–40	275–1070
Summary	43	20–75	22–39	35–153	24–42	165–1070

The number of felled trees of each examined woody species was proportional to its representation in the forests of Slovakia according to the age and site indices expressing the level of production through the average tree height (m), which the forest stand would reach at the age of 100 years. Biomass samples were taken from the base of the trunk, from the middle part of the trunk, from the trunk in the middle part of the tree crown and from the branches. Samples taken from 3 parts of the tree trunk were then separated into wood and bark. In the case of samples taken in the middle part of the crown from the middle part of the branches, the bark did not separate from the wood.

To determine the basic density, the volume of fresh samples was measured in 2000 mL calibrated cylinders with an accuracy of 1 mL. All samples were then dried at 103 $\pm$ 2 °C to a constant weight to the nearest 0.01 g [25]. For calorimetric determination, the samples were dried at 103 $\pm$ 2 °C and ground using an SM 100 cutting mill (Retsch). The gross calorific value was determined using an IKA C-4000 calorimeter (program C-402). Two determinations were performed on each sample with an accuracy of up to 120 J [24].

2.2. Calculation of Energy Reserves

The energy reserves of Norway spruce (*Picea abies* (L.) H.Karst.), Silver fir (*Abies alba* Mill.), Scots pine (*Pinus sylvestris* L.) and European larch (*Larix decidua* Mill.) stands were determined based on the volume production of above-ground biomass fractions taken from the yield table models, average basic densities and gross calorific value of dry mass of biomass fractions. The yield tables are in the form of mathematical models and simulate the biomass volume BV depending on the age t and the site index q of the forest stand, Formula (1):

$$BV\ [\mathrm{m}^3\ \mathrm{ha}^{-1}] = f\ (t, q) \tag{1}$$

Data on the volume production of spruce, fir and pine fractions were taken from Czechoslovak yield tables [24,25]. Data on volume production of larch was taken from yield tables of Schober [26], modified by Petráš [27]. The yield tables correspond to fully dense stands, which, however, do not reach the density of natural stands due to silvicultural interventions. They report the volume of wood, bark and branches of trees for the main stand, secondary crop, total production, total mean increment and total current annual increment. The total production of the stand is expressed by Formula (2):

$$TP_t = MS_t + \sum\nolimits_0^t SC \tag{2}$$

where

TP_t is the total production of the stand at age t,
MS_t is the volume of the main stand at age t,
$\sum_0^t SC$ is the sum of the production of secondary crops (thinnings) aged 0 to t years.

Total mean increment of the stand is expressed by Formula (3):

$$TMI_t = \frac{TP_t}{t} \tag{3}$$

where

TMI_t is the total mean increment of the stand at age t,
TP_t is the total production of the stand at age t,
t is the age of the stand.

Total current annual increment of the stand is expressed by Formula (4):

$$TCAI_t = \frac{TP_{t+5} - TP_{t-5}}{10} \tag{4}$$

where

$TCAI_t$ is the total current annual increment of the stand at age t,

TP_{t+5}, TP_{t-5} is the total production of the stand at age $t + 5$ and $t - 5$.

The energy density of each tree biomass fraction was calculated using Formula (5):

$$ED\ [\mathrm{GJ\ m^{-3}}] = BD\ [\mathrm{kg\ m^{-3}}]\ GCV\ [\mathrm{J\ g^{-1}}]\ 10^{-6} \quad (5)$$

where

ED [GJ m^{-3}] is energy density of biomass fraction taken from Petráš [24],
BD [kg m^{-3}] is basic density of biomass fraction [25],
GCV [J g^{-1}] is gross calorific value of dry matter of biomass fractions.

The energy reserve of the coniferous stand was calculated as the sum of the energy stored in the fractions of wood and bark of the trunk and branches of the trees. The resulting model expresses the energy reserve ER of spruce, fir, pine and larch stands depending on their age t and site index q, according to Formula (6):

$$ER\ [\mathrm{GJ\ ha^{-1}}] = f\ (t, q) \quad (6)$$

The energy stored in the above-ground biomass of coniferous stands was calculated using a computer program created in the Pascal language (unpublished). The program multiplied the volumes of wood, bark and branches of the main stand and thinnings, total mean increment and total current annual increment (taken from yield tables [27–29]) by average energy density values (taken from Petráš [24]). As mentioned above, the energy density values were calculated for each biomass fraction as the product of the values of basic density values and gross calorific values, which were determined in biomass samples taken from 43 representative coniferous stands selected in the territory of Slovakia, taking into account their age and site index.

2.3. Solar Energy Use Efficiency

The efficiency of the use of solar radiation by forest stands was calculated on the basis of average values of global solar radiation, which were found at the Meteorological Observatory of the Geophysical Institute of the Slovak Academy of Sciences in Mlyňany (48°19′ S, 18°20′ E, 195 m a.s.l.). Ostrožlík [30] reports an average global radiation 43,621.2 GJ ha^{-1} year^{-1} for the observatory site for the years 1970–2002.

The efficiency of the use of solar energy by forest stands was calculated as the proportion of the total current annual increment to the average global radiation in the months of May to September according to Formula (7):

$$SEUE_t = \frac{TCAI_t}{AAGR} \quad (7)$$

where

$SEUE_t$ is the efficiency of the use of solar energy by the stand at age t,
$TCAI_t$ is the energy of total current annual increment of stand at age t,
$AAGR$ is average global solar radiation from May to September.

2.4. Statistical Analysis

The variability of the energy characteristics of the above-ground biomass of stands of 4 woody species (spruce, fir, pine and larch) was evaluated using the Statistica 9 program (StatSoft, 2008). One-way ANOVA followed by Tukey's test were used to determine significant differences in values of energy characteristics of woody species in 2 main growth periods (45–80 and 85–120 years) of the stands. Results were expressed as mean (x) and standard deviation (±SD). Differences between means were considered significant when they occurred at $p < 0.05$.

3. Results

3.1. Development of the Shares of Energy Reserves in Above-Ground Biomass Fractions of Coniferous Stands

The shares of energy reserves in above-ground biomass fractions are not the same during the economic cycle of coniferous stands (Figure 2).

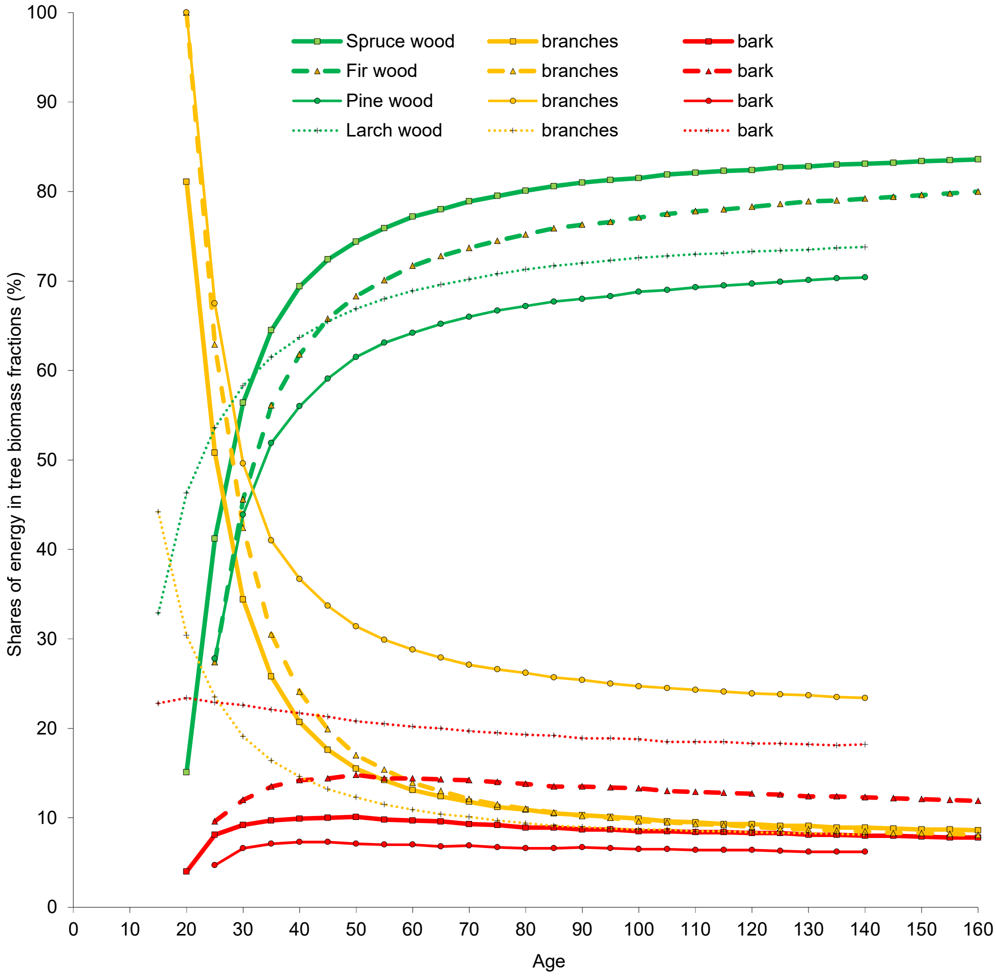

Figure 2. Development of shares of energy reserves in above-ground biomass fractions from the total energy reserves of coniferous stands with a medium site index (30 for spruce, fir and larch; 24 for pine).

As the age of the stands increased, the share of energy reserves in wood increased and their share in the branches and bark of stands older than 40–50 years decreased. The share of energy reserves is usually the highest in wood or branches of stands younger than 30 years and the lowest in the bark of woody species. The only exception is larch stands older than 25 years, in the bark of which there are greater reserves of energy than in the branches. Pine wood and bark have the lowest share of energy reserves of all woody species, and the highest share is in pine branches. On the other hand, the highest share of energy reserves is in spruce wood and larch bark.

The development of the shares of energy reserves in the biomass fractions of stands interesting from the point of view of forest management (premature, mature, overmature stands) can be seen in Table 2.

Table 2. The development of shares of energy reserves in biomass fractions of stands with a medium site index (30, in the case of pine 24).

Woody Species		Spruce			Fir			Pine			Larch		
Age of Stand (Years)		40	80	120	40	80	120	40	80	120	40	80	120
Biomass fraction (%)	wood	69.4	80.1	82.4	61.8	75.2	78.3	56.0	67.2	69.7	63.7	71.3	73.3
	branches	20.7	10.9	9.3	24.1	11.0	9.0	36.7	26.2	23.9	14.6	9.4	8.4
	bark	9.9	8.9	8.3	14.2	13.8	12.7	7.3	6.6	6.4	21.7	19.3	18.3

3.2. Development of Energy Reserves in the Total Mean Annual Increments of Coniferous Stands

Energy reserves in the total mean annual increments of coniferous stands increase with increasing site index (Figure 3).

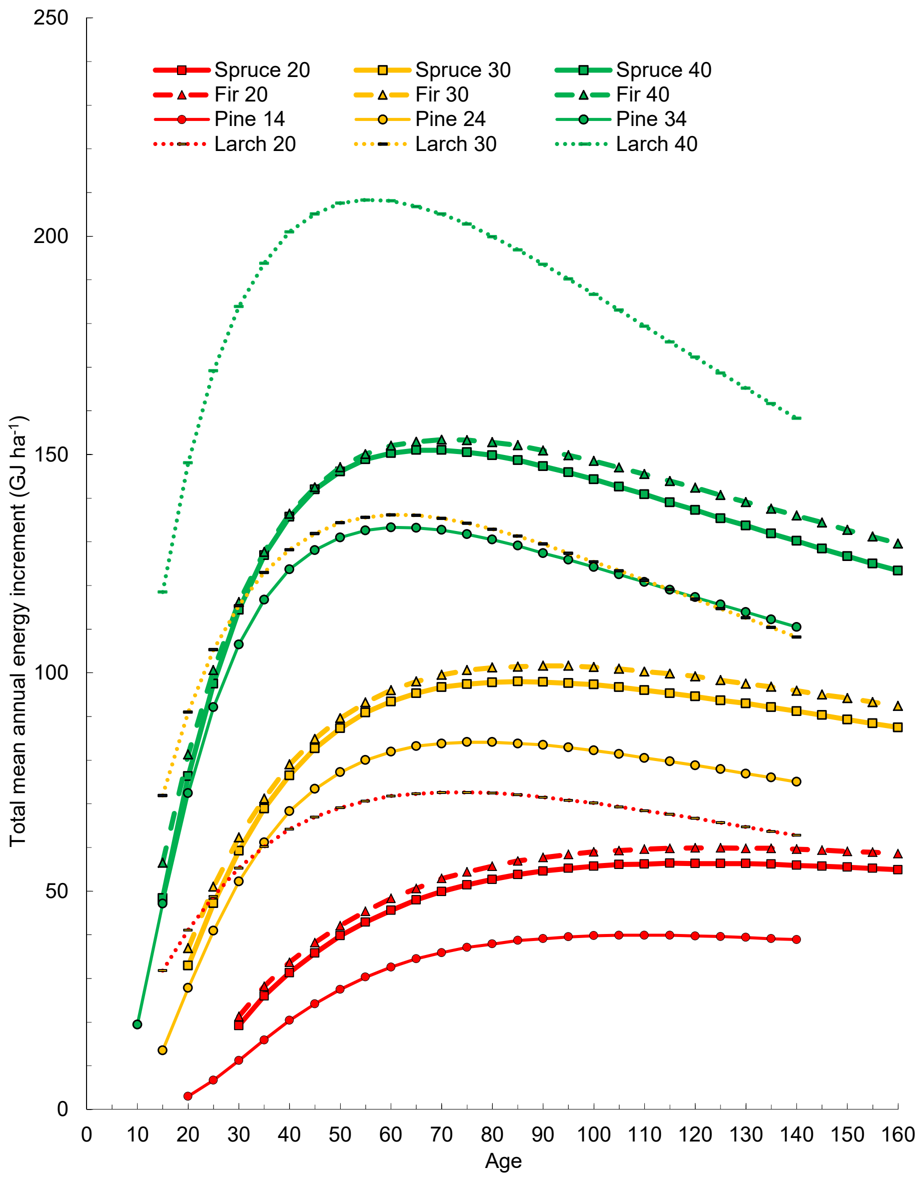

Figure 3. Development of energy reserves in the total mean increments of coniferous stands depending on their age and site index (20, 30, 40 for spruce, fir and larch; 14, 24, 34 for pine).

Stands with the lowest site index usually grow up to the age of 115–125 years; only larch stands grow up to the age of 80 years. In stands with higher site indices, they increase to the age of 90–95 years (spruce and fir stands) or 60–80 years (pine and larch stands).

The energy reserves in the total mean annual increment of coniferous stands with low, medium and high site index culminate at the age of 55–120 years, when they reach 40–210 GJ ha^{-1}. Energy reserves in the increments of spruce stands peak at the age of 70–115 years, when they reach 55–150 GJ ha^{-1}, fir stands at the age of 70–120 years, when they reach 60–155 GJ ha^{-1}, pine stands at the age of 60–110 years, when they reach 40–135 GJ ha^{-1} and larch stands at the age of 55–70 years, when they reach 75–210 GJ ha^{-1}. As the age of the stands increases, the energy reserves in the total mean annual increments of coniferous stands decrease slightly.

The development of the energy reserves in total mean annual increments of stands from the point of view of forest management can be seen in Table 3. Larch stands have the highest energy reserves in total mean annual increments, followed by fir, spruce and pine stands.

Table 3. The development of energy reserves in total mean annual increments of stands with low, medium, and high site index.

Woody Species		**Spruce**			**Fir**			**Pine**			**Larch**		
Age of Stand (Years)		**40**	**80**	**120**	**40**	**80**	**120**	**40**	**80**	**120**	**40**	**80**	**120**
Total mean increment (GJ ha^{-1})	low SI *	31.3	52.7	56.3	33.7	55.7	59.9	20.4	37.9	39.7	64.2	72.5	66.7
	medium SI *	76.5	97.8	94.6	79.0	101.2	99.2	68.3	84.1	78.8	128.2	132.9	116.9
	high SI *	135.7	149.8	137.5	136.4	152.8	142.4	123.7	130.5	117.3	201.0	199.0	172.3

* SI—Site index.

3.3. Development of Energy Reserves in the Total Current Annual Increments of Coniferous Stands

The energy reserves in the total current annual increment of coniferous stands with low, medium and high site index culminate at the age of 25–65 years, when they reach 60–260 GJ ha^{-1} (Figure 4). This is 25–50 years earlier than in the case of the total mean increment. Energy reserves in increments of spruce stands peak at the age of about 30–60 years, when they reach 75–200 GJ ha^{-1}, fir stands at the age of 35–65 years, when they reach 80–200 GJ ha^{-1}, pine stands at the age of 30–55 years, when they reach 60–180 GJ ha^{-1} and larch stands at the age of 25–35, when they reach 90–260 GJ ha^{-1}.

The decrease in energy reserves in the total current annual increment of coniferous stands with the lowest site index begins in spruce and fir stands at the age of 65–70 years, pine stands at the age of 60 years and larch stands at the age of 40 years. In stands with higher site indices, it starts already at the age of 45 years (spruce, fir, pine stands) or at the age of 35 years (larch stands).

The largest energy reserves are in the total current annual increments of larch stands, but only up to the age of 70 years, when higher energy reserves are in the increments of spruce and fir stands with the lowest site index. Spruce stands with a site index 30 older than 95 years and fir stands with site indices 30 and 40 older than 85–90 years also have higher energy reserves in increments.

The development of the energy reserves in the total current annual increments of stands interesting from the point of view of forest management can be seen in Table 4.

3.4. Development of Energy Reserves in the Above-Ground Biomass of Coniferous Stands

The development of energy reserves in the above-ground biomass of fully stocked coniferous stands varies depending on the woody species, stand age and the site indices (Figure 5). With increasing age of coniferous stands, it gradually increases along the growth curves of a characteristic shape.

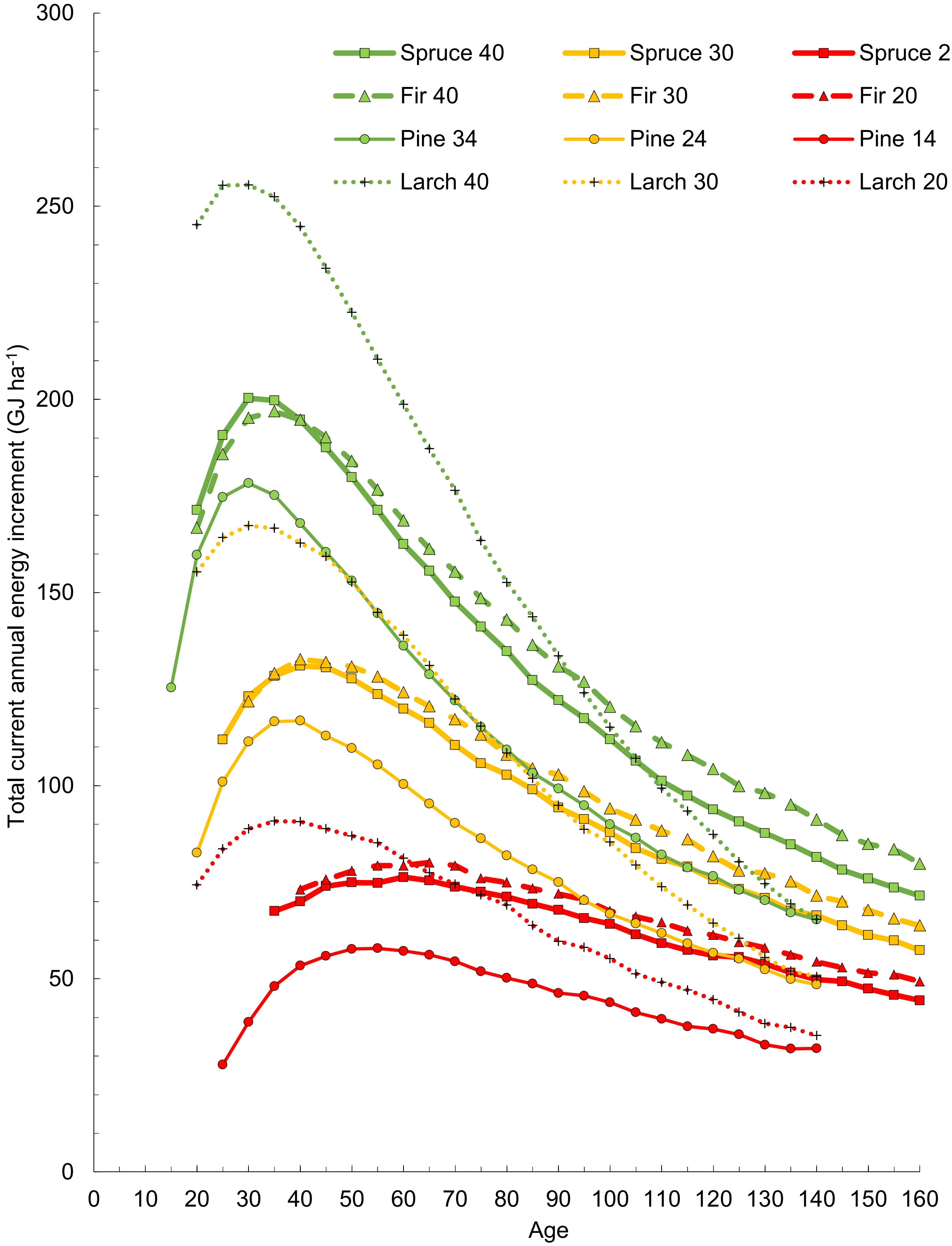

Figure 4. Development of energy reserves in the total current annual increments of coniferous stands depending on their age and site index (20, 30, 40 for spruce, fir and larch; 14, 24, 34 for pine).

Table 4. The development of energy reserves in the total current annual increments of stands with low, medium and high site index.

Woody Species		Spruce			Fir			Pine			Larch		
Age of Stand (Years)		40	80	120	40	80	120	40	80	120	40	80	120
Total current annual increment (GJ ha^{-1})	low SI *	70.0	71.2	56.0	73.1	74.9	61.3	54.3	50.2	37.0	90.7	69.1	44.6
	medium SI *	131.0	102.8	75.7	132.7	108.0	81.7	116.8	81.9	56.7	162.8	108.4	64.4
	high SI *	194.7	134.8	93.8	194.7	143.0	104.3	167.9	109.3	76.6	244.7	152.6	87.3

* SI—Site index.

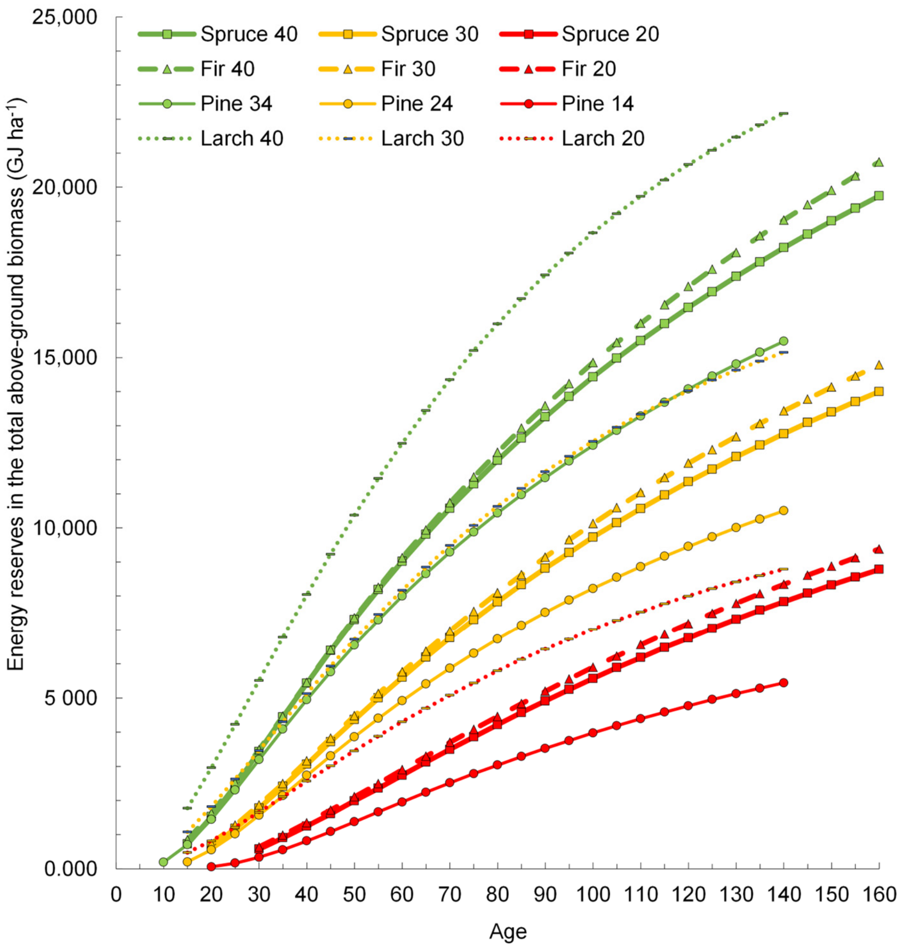

Figure 5. Development of energy reserves in the total above-ground biomass of coniferous stands depending on the stand age and site index (20, 30, 40 for spruce, fir and larch; 14, 24, 34 for pine).

The development of the energy reserves in the above-ground biomass of stands from the point of view of forest management can be seen in Table 5.

As the age of the stands increases, energy reserves do not increase uniformly. At the age of 40 to 80 years, they grow faster than at the age of 80 to 120 years. In these two time periods, the average energy reserves of coniferous stands (average for site indices) increased by (GJ ha^{-1}): spruce stands 4762 and 3519, fir stands 4938 and 3797, pine stands 3902 and 2696, larch stands 5562 and 3425. In the first growth period, the energy reserves in the biomass of the stands (compared to the second growth period) were thus higher by (GJ ha^{-1}): spruce stands 1243, fir stands 1141, pine stands 1206 and spruce stands 2137. This is consistent with the fact that above-ground biomass energy increases steadily with increasing stand age, but the total mean increment peaks at a certain stand age and then declines.

Table 5. The development of the energy reserves in the above-ground biomass of stands with low, medium and high site index.

Woody Species		Spruce			Fir			Pine			Larch		
Age of Stand (Years)		**40**	**80**	**120**	**40**	**80**	**120**	**40**	**80**	**120**	**40**	**80**	**120**
Total current annual increment (GJ ha^{-1})	low SI *	1251	3060	5430	1349	3159	5454	815	2733	4948	2567	5129	8040
	medium SI *	4218	7824	11,985	4460	8097	12,220	3035	6731	10,437	5798	10,635	15,989
	high SI *	6758	11,355	16,470	7184	11,899	17,085	4767	9451	14,073	8000	14,026	20,671

* SI—Site index.

The differences in the above-ground biomass energy reserves of 40, 80 and 120-year-old spruce, fir and larch stands compared to the lowest energy reserves of pine stands increase towards older stands. However, they can also decrease in percentage terms, as in the case of the lowest site index of spruce and fir stands and all site indices of larch stands.

3.5. The Development of the Efficiency of the Use of Solar Energy by Coniferous Stands

The efficiency of the use of solar energy by coniferous stands is shown in Figure 6. The curves constructed in relation to stand age and site index have a very similar shape to the curves of the total current annual energy increment of coniferous stands (Figure 4). The efficiency of the use of solar energy by coniferous stands with low site index reaches 0.19%–0.32% and peaks at the age of 30–70 years, in the case of medium site index it reaches 0.40%–0.59% and peaks at the age of 25–45 years, and in the case of high site index, it reaches 0.62%–0.90% and peaks at the age of 25–40 years. It increases from low to high site index and with the age of stands and after reaching the culmination it decreases significantly. The efficiency of the use of solar energy practically peaks at the age of reaching the maximum energy reserve in total current annual increment of coniferous stands.

The efficiency of the use of solar energy by spruce and fir stands with a site index of 20 reaches 0.26%–0.27% and 0.27%–0.28%, respectively, and peaks at the age of 45–70 years. In the case of spruce and fir stands with a site index of 30, it reaches 0.45%–0.46% and 0.46%–0.47%, and peaks at the age of 35–50 years, and in stands with site index 40 reaches 0.69%–0.71% and peaks at the age of 30–40 years. The efficiency of the use of solar energy by pine stands with site indices 14, 24 and 34 reaches 0.19%–0.20%, 0.40%–0.41% and 0.62%–0.63%, respectively, and peaks at the age of 40–70, 35–45 and 25–35 years, respectively. The maximum efficiency of solar energy utilisation by larch stands with site indices of 20, 30 and 40 is as follows: 0.31%–0.32% at the age of 30–40 years, 0.58%–0.59% at the age of 25–35 years and 0.89%–0.90% at the age of 25–35 years.

The development of the efficiency of solar energy utilization by coniferous stands from the point of view of forest management can be seen in Table 6. The decrease in the efficiency of solar energy use by the spruce and fir stands with the lowest site index begins at the age of 60–70 years, in the case of pine stands at the age of 45–65 years and larch stands at the age of 45–50 years. In stands with a higher site index, the efficiency of solar energy use decreases already after reaching the age of 30–40 years.

3.6. Variability of Energy Characteristics of Above-Ground Biomass of Coniferous Stands

The variability of energy characteristics of the above-ground biomass of the investigated stands of the woody species is shown in Table 7. The average shares of energy are the highest in the wood of spruce stands and the lowest in the wood of pine stands. The shares of energy in the second growth period of the stands are higher for all woody species. The shares of energy in the branches are the highest in pine stands and the lowest in larch stands, with a maximum in the first growth period of the stands. In the case of bark, on the other hand, the highest share of energy is in larch stands and the lowest in pine stands, also with a maximum in the first growth period of the stands. The shares of energy in the biomass fractions of the stands of the above-mentioned woody species are significantly different in all cases.

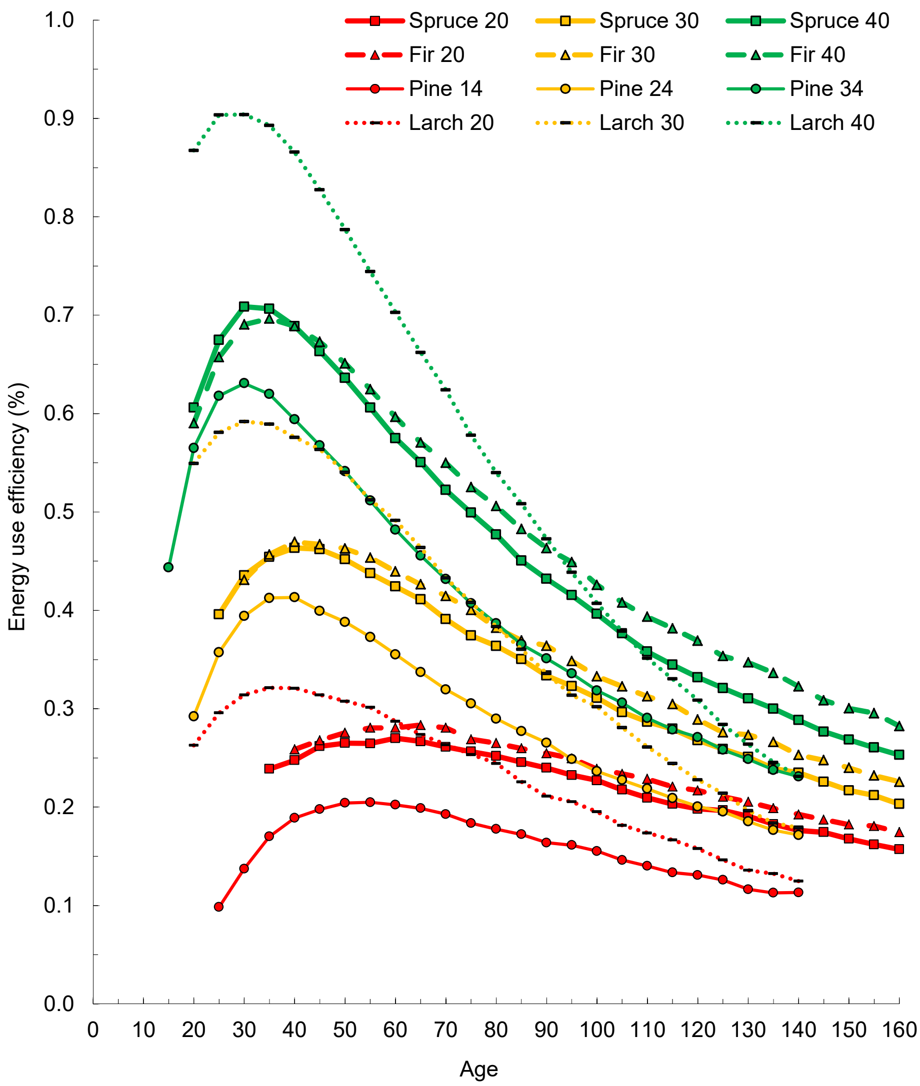

Figure 6. Development of the efficiency of the solar energy use by coniferous stands depending on the age of the stand and the site index (20, 30, 40 for spruce, fir and larch; 14, 24, 34 for pine).

Table 6. The efficiency of solar energy utilization by coniferous stands with low, medium and high site index.

Woody Species		**Spruce**			**Fir**			**Pine**			**Larch**		
Age of Stand (Years)		**40**	**80**	**120**	**40**	**80**	**120**	**40**	**80**	**120**	**40**	**80**	**120**
Efficiency of solar energy utilization (%)	low SI *	0.25	0.25	0.20	0.26	0.26	0.22	0.19	0.18	0.13	0.32	0.24	0.16
	medium SI *	0.46	0.36	0.27	0.47	0.38	0.29	0.41	0.29	0.20	0.58	0.38	0.23
	high SI *	0.69	0.48	0.33	0.69	0.51	0.37	0.59	0.39	0.27	0.87	0.54	0.31

* SI—Site index.

Table 7. Variability of energy characteristics of coniferous stands. ANOVA, Tukey's test. Significantly different mean values ($p < 0.01$) of energy characteristics are indicated by different letters (^{a,b,c}).

Energy Characteristic	Forest Stand	Growth Period	Biomass Fraction					
			Wood	Branches	Bark	Wood	Branches	Bark
		(Years)	x			SD		
Shares of energy reserves (%) in above-ground biomass fractions of forest stands with a medium site index (30 for spruce, fir and larch; 24 for pine)	*Picea abies*	45–80	77.05 ^{a}	13.34 ^{b}	9.58 ^{c}	±2.66	±2.31	±0.41
		85–120	81.64 ^{a}	9.81 ^{b}	8.55 ^{c}	±0.65	±0.46	±0.20
	Abies alba	45–80	71.51 ^{b}	14.23 ^{c}	14.29 ^{b}	±3.25	±3.05	±0.30
		85–120	77.19 ^{b}	9.68 ^{b}	13.14 ^{b}	±0.86	±0.55	±0.32
	Pinus sylvestris	45–80	64.13 ^{a}	28.95 ^{a}	6.93 ^{b,c}	±2.78	±2.59	±0.23
		85–120	68.79 ^{b,c}	24.70 ^{a}	6.51 ^{b,c}	±0.73	±0.63	±0.11
	Larix decidua	45–80	68.90 ^{b}	10.94 ^{b}	20.16 ^{a}	±2.00	±1.32	±0.68
		85–120	72.60 ^{c}	8.71 ^{c}	18.70 ^{a}	±0.56	±0.25	±0.30
Total mean annual energy increment of coniferous stands (GJ ha^{-2})	Site index (*Pinus*)		20 (14)	30 (24)	40 (34)	20 (14)	30 (24)	40 (34)
			x			SD		
	Picea abies	45–80	45.76 ^{c}	92.69 ^{c}	148.70 ^{c}	±5.92	±5.40	±3.15
		85–120	55.54 ^{c}	96.68 ^{c}	143.25 ^{c}	±0.93	±1.26	±4.03
	Abies alba	45–80	48.45 ^{b,c}	95.38 ^{c}	150.51 ^{c}	±6.18	±5.77	±3.88
		85–120	58.83 ^{b,c}	100.76 ^{b,c}	147.51 ^{c}	±1.08	±0.90	±3.43
	Pinus sylvestris	45–80	32.50 ^{b}	80.96 ^{b}	131.64 ^{b}	±4.85	±3.89	±1.75
		85–120	39.56 ^{b}	81.60 ^{b}	123.28 ^{b}	±0.44	±1.82	±4.13
	Larix decidua	45–80	71.06 ^{a}	134.60 ^{a}	205.46 ^{a}	±2.05	±1.55	±2.92
		85–120	69.58 ^{a}	124.28 ^{a}	184.75 ^{a}	±1.91	±5.06	±8.67

Table 7. *Cont.*

Energy Characteristic	Forest Stand	Growth Period (Years)	Wood	Branches	Bark	Wood	Branches	Bark
			x			SD		
	Site index (*Pinus*)		20 (14)	30 (24)	40 (34)	20 (14)	30 (24)	40 (34)
			x			SD		
Total current annual energy increment of coniferous stands (GJ ha^{-2})	*Picea abies*	45–80	74.11 [b]	117.15 [b]	160.03 [a]	±1.64	±10.16	±18.70
		85–120	62.65 [c]	86.50 [b]	109.70 [b]	±4.91	±8.04	±12.04
	Abies alba	45–80	77.81 [b]	121.76 [b]	165.95 [b]	±2.00	±8.61	±16.90
		85–120	67.23 [c]	93.40 [b]	119.16 [b]	±4.44	±8.10	±11.48
	Pinus sylvestris	45–80	55.19 [b]	97.78 [a]	133.68 [a]	±2.81	±11.22	±18.18
		85-120	42.51 [a]	66.54 [a]	88.93 [a]	±4.27	±7.59	±9.68
	Larix decidua	45–80	79.36 [b]	134.12 [b]	193.14 [b]	±7.33	±18.03	±28.52
		85–120	53.61 [b]	82.20 [b]	112.94 [b]	±6.69	±12.92	±19.85
	Site index (*Pinus*)		20 (14)	30 (24)	40 (34)	20 (14)	30 (24)	40 (34)
			x			SD		
Energy reserves in the total above-ground biomass of coniferous stands (GJ ha^{-2})	*Picea abies*	45–80	2923.38 [b]	5847.13 [b]	9319.63 [b]	±915.24	±1438.56	±1957.27
		85–120	5701.88 [c]	9897.13 [c]	14,639.38 [c]	±766.94	±1056.72	±1341.50
	Abies alba	45–80	3094.38 [b]	6020.00 [b]	9442.00 [b]	±964.64	±1498.90	±2031.23
		85–120	6040.38 [c]	10,317.88 [c]	15,084.00 [c]	±822.91	±1145.02	±1454.80
	Pinus sylvestris	45–80	2082.25 [b]	5099.50 [b]	8233.13 [b]	±685.32	±1199.90	±1634.65
		85–120	4057.75 [b]	8344.50 [b]	12,590.25 [b]	±520.01	±811.27	±1085.66
	Larix decidua	45–80	4460.00 [a]	8415.50 [a]	12,818.25 [a]	±974.57	±1647.32	±2369.49
		85–120	7112.25 [a]	12,685.00 [a]	18,842.25 [a]	±654.44	±1005.28	±1375.93

Table 7. *Cont.*

Energy Characteristic	**Forest Stand**	**Growth Period**	**Biomass Fraction**					
			Wood	**Branches**	**Bark**	**Wood**	**Branches**	**Bark**
		(Years)	**x**			**SD**		
	Site index (*Pinus*)		20 (14)	30 (24)	40 (34)	20 (14)	30 (24)	40 (34)
			x			SD		
Energy use efficiency of coniferous stands (%)	*Picea abies*	45–80	0.261 [b]	0.413 [b]	0.566 [b]	±0.006	±0.037	±0.066
		85–120	0.223 [c]	0.306 [b]	0.389 [b]	±0.018	±0.027	±0.044
	Abies alba	45–80	0.275 [b]	0.430 [b]	0.588 [c]	±0.008	±0.032	±0.057
		85–120	0.238 [c]	0.329 [b]	0.421 [b]	±0.015	±0.029	±0.040
	Pinus sylvestris	45–80	0.194 [a]	0.348 [a]	0.474 [b]	±0.009	±0.040	±0.063
		85–120	0.150 [b]	0.238 [a]	0.316 [a]	±0.015	±0.028	±0.035
	Larix decidua	45–80	0.279 [b]	0.473 [b]	0. 683 [a]	±0.027	±0.064	±0.102
		85–120	0.191 [a]	0.290 [b]	0.400 [b]	±0.025	±0.046	±0.070

The energy reserves of total mean annual energy increment of coniferous stands are the highest in larch stands and the lowest in pine stands, regardless of site index. In the second growth period, they are higher in stands of woody species with a low (20, for pine 14) and medium (30, for pine 24) site index, except for larch. On the other hand, in stands with a high site index (40, for pine 34) the energy reserves of increments decrease in the second growth period. The energy reserves of the increments also increase with the increasing site index of the stands. The energy reserves of the increments of the above-mentioned woody species are significantly different.

The energy reserves of total current annual energy increment are higher in the first growth period, regardless of site index of stands. The energy reserves of the increments also increase with the increasing site index of the stands. The energy reserves of increments of spruce, fir and spruce stands with a low site index are very similar and, with the exception of larch, are significantly lower in the second growth period. The lowest energy reserves of increments are in pine stands. The highest energy reserves of increments of stands with a medium and high site index are in larch stands, and the lowest are in pine stands. The energy reserves of the increments of the above-mentioned woody species differ significantly.

The energy reserves of total above-ground biomass of coniferous stands are higher in the second growth period, regardless of site index of stands. They also increase with the increasing site index of stands. The highest energy reserves are in larch stands and the lowest in pine stands. The differences are significant, regardless of site index of stands. However, the differences in energy reserves calculated for the two growth periods of stands are significantly different only in case of spruce and fir stands.

The efficiency of using solar energy is higher in the first growth period of coniferous stands, regardless of their site index, and it is also higher in stands with a higher site index. The difference compared to the efficiency of the use of solar energy in the second growth period of coniferous stands is significant in the case of spruce stands with a low site index, and fir, pine and larch stands with a low and high site index. Larch stands have the highest use of solar energy, followed by fir and spruce stands, and pine stands have the lowest use of solar energy. The efficiency of using solar energy is significantly different for larch and pine stands with a low and high site index.

4. Discussion

Models potentially integrate a wide range of system knowledge and present scenarios of variables important for any management decision [2]. Although yield tables were already the origin of forest models in the 17th century, the estimation of wood production continues to be one of the main goals of modelling [1]. Many of the new models are mainly focused on the understanding of growth processes, carbon cycles, estimation of biomass and energy using allometric equations, distribution of radiation in a vegetation canopy, tree mortality and so on. However, there is a lack of studies aimed at predicting the development of energy reserves in fractions, increments and the total biomass of forest stands during their entire economic cycle.

Oszlányi [31] was the first author in Slovakia to publish work focusing on the analysis of biomass production and its energy equivalent of the tree layer of forest ecosystems. The author found an energy reserve of 5385.322 GJ ha^{-1} in the above-ground biomass of 80-year-old spruce stands located in the Malé Karpaty Mts. The stated value is comparable to the energy reserve we found in 80-year-old spruce stands with lower and medium site index (4218; 7824; 11,985; on average 8009 GJ ha^{-1}). The energy reserves of spruce stands with the highest site index are more than twice as much. The total current annual increment of spruce stands determined in the Malé Karpaty Mts reaches 180,910 GJ ha^{-1} and is higher compared to our results (71.2; 102.8; 134.8; on average 102.93). Oslányi [31] also reports the energy reserves of 53–84-year-old pine stands in the range from 3009.066 to 3790.358 GJ ha^{-1} and the energy reserves of total current annual increment of stands in the range of 98,140 to 146,733 GJ ha^{-1}. The energy reserves we found in 55–85-year-old pine stands with a low, medium and high site index (2497.143; 5822.286; 9217.000; on average 5845.476 GJ ha^{-1}) are considerable higher, while the energy reserves of total current annual increments of stands are slightly lower (53.800; 91.129; 122.757; on average 89.229 GJ ha^{-1}).

Danilov and Kharlanov [32] focused on the research of mature coniferous stands of natural origin, unaffected by economic activity, located in the boreal zone of Northwest Russia. The authors found that stands with a proportion of pine 70%–90% and spruce 80%–90% have the largest growing stock and stem mass. Energy reserves in the stem mass of stands with a predominance of spruce reached 1873.326–4546.055 (on average 2999.297) GJ ha^{-1}, and in the case of a predominance of pine, 2987.507–4108.825 (on average 3532.165) GJ ha^{-1}. The above values are comparable to the average energy reserves of 40-year-old Central European spruce and pine stands. Mature 70–80-year-old spruce stands (3856.333; 7297.333; 11,282.33; on average 7478.667) and pine stands (2778.0; 6302.333; 9866.667; on average 6315.667) with a low, medium and high site index are significantly higher. In the above-ground biomass of Scots pine monocultures in the Dnepropetrovsk Region (Northern Steppe of Ukraine), the maximum energy reserves were found in 61–80-year-old stands [33]. The energy reserves in the biomass fractions of pine stands reach (GJ ha^{-1}): wood 1995.09, bark 211.81, branches 147.06, needles 63.69. The total energy reserves in these pine stands reach 2417.05 GJ ha^{-1} and compared to our values found in 60–80-year-old pine stands with low, medium and high site index (1379.80; 3843.40; 6511.20; on average 3911.47 GJ ha^{-1}), they are about a third lower. Energy reserves in 81–100-year-old Scots pine monocultures are somewhat lower (similarly high as energy reserves in the 41-61 age group) and amount to (GJ ha^{-1}): wood 1534.60, bark 145.62, branches 143.83 and needles 52.24. The total energy reserves reach 1876.29 GJ ha^{-1} and compared to our values found in 80–100-year-old pine stands with low, medium and high site index (3911.47; 5867.2; 7486.2; on average 5754.96 GJ ha^{-1}), they are three times lower. We could not find published data on the energy reserves of the above-ground biomass of fir and larch stands.

The average annual energy value of the wood in the total area of forest resources of the State Forests National Forest Holding (PGLLP) in Poland was 0.07 GJ ha^{-1}, whereas the highest value was 0.14 GJ ha^{-1}. For the years 2018 and 2021, the share of the energy potential of biomass from renewable sources increased significantly in Poland. It was possible to demonstrate the dominant role of pine biomass, whose energy potential was estimated at about 300,000 GJ (equivalent to 64% of the annual energy potential of the forest biomass harvested by the State Forests) [34].

It is also useful to know the ability of woody plants to use global solar radiation. Pretzsch [22] states that the efficiency of the use of solar energy by spruce and pine stands is 0.8%–0.9%. The values found by us for 30-year-old spruce (0.71%) and pine (0.63%) stands with the highest habitat index are the closest to the stated values, but the average values found for 80–100-year-old stands with a low, medium and high site index are considerably lower (spruce stands: 0.24, 0.33, 0.44, on average 0.34; pine stands 0.17, 0.27, 0.35, on average 0.26). In the above case, however, it reports a year-round global radiation of 36,000 GJ ha^{-1}, while in our case we only considered global radiation during the growing season (May to September), i.e., with a value of 28,267 GJ ha^{-1}. In addition, this author considered annual increments only for round wood with bark (merchantable volume) from the national forest inventory. However, it is known that the volume of the whole above-ground tree biomass is higher; for coniferous tree species about 8%–10% and for broadleaved tree species 12%–15%. Oszlányi [31] found that the solar energy use efficiency by 80-year-old spruce stands is 0.57%, and in 53–84-year-old pine stands it is 0.39%. The equivalent values found by us (0.36%, 0.32%) are somewhat lower. Larcher [4] states a limit of 2% for forest stands, but only values below 1% for most tree species. Bublinec et al. [35] also report that beech ecosystems in Central Europe effectively utilize less than 1% of solar energy during the photosynthetic activity period. However, in the case of 21-year-old *Picea omorika* plantations in Great Britain, the accumulation of available solar radiation reaches up to 2.7% per year [36]. However, this value seems too high compared to our findings for 20-year-old spruce stands (0.61).

Boardman [37] states that the global annual productivity of photosynthesis equals 3 × 1021 J of stored solar energy, which is 10-fold higher than present world consumption of energy. The overall efficiency of solar energy conversion is 0.15%. Maximum short-term growth rates of high yielding crops represent solar energy conversion efficiencies of 2.7%–4.6%, but annual productivities are considerably lower (0.16%–1.6%). Forests show average efficiencies of 0.2%–0.3% in the Northern Hemisphere and even lower ones in Australia. The maximum conversion efficiency of solar energy to biomass is 4.6% for C3 photosynthesis at 30 °C and today's 380 ppm atmospheric [CO_2], but 6% for C4 photosynthesis. This advantage over C3 will disappear as atmospheric [CO_2] nears 700 ppm [15].

In order to more accurately assess the efficiency of solar energy storage by individual tree species, more detailed and extensive research would be needed, in particular as regards the calorific value of all components, including leaf biomass.

5. Conclusions

A large part of forest biomass is stored in tree species; therefore, understanding the factors regulating biomass accumulation during entire economic cycle of forest stands is the key to predicting the development of energy reserves and energy potential of forests. In this work, the energy reserves in the total mean increments of coniferous stands increased with increasing site index. The highest energy reserves were in the total mean increment of larch stands, followed by fir, spruce and pine stands. The energy reserves in the total current annual increment of coniferous stands culminated 25–50 years earlier than in the case of the total mean increment. As coniferous stands age, the energy reserves in their above-ground biomass increase, and at the same time, the efficiency of the use of solar energy by the stands significantly decreases. The efficiency curves of the use of solar energy practically peak at the age of reaching the maximum energy reserve in the total current annual increment of coniferous stands.

In this work, we focused mainly on modelling the development of above-ground biomass energy reserves of economically important coniferous woody species in Slovakia. The assessment of above-ground biomass stocks in the coniferous forests is important both for the inventory of wood, bioenergy and carbon, as well as for wildfire risk determination. The data obtained can be useful in planning the economic use of energy stored in whole trees and stands. The obtained data can also contribute to the understanding of the interrelationships of the basic components of forest communities and to the formation of an idea of the functioning of forest ecosystems.

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