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A Production Planning Model for Biorefineries with biomass perishability and biofuel transformation

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A biomass processing unit that treats different types of biomass to transform them either into bioenergy or biofuel is considered. A production planning problem over a discrete-time horizon is modeled and solved. Both biomass and biofuel can be stored. Storage of biofuel serves to match the supply with the demand of both bioenergy and biofuel. Deterioration of biomass, which was rarely studied in the bioenergy production literature, is modeled and its impact on storage decisions is analyzed.

The proposed model has two main characteristics: i) controlling inventory of the perishable biomass while considering different ages for the stored biomass and ii) biomass can be transformed into either bioenergy or biofuel, which in turn can be stored and then transformed into bioenergy. The applicability of the developed model is shown through several numerical experiments. The results show that first, perishability can lead to profit losses that cannot be neglected. Second, there is a threshold value on the perishability rate above which perishability does not have any longer impact on the profit. Third, storage and transformation of biofuel results in considerable increase in profit and smoother production at the facility even when there is a high fluctuation in price and demand. Fourth, when the decision maker imposes a maximum age on biomass to enhance quality and reduce health risks, the model provides guidelines on how to make this decision with the lowest impact.

1. Introduction

The increasing concerns related to the energy demand and environmental problems made by using fossil fuels have led scientists to think about renewable energy as a clean alternative. In particular, bioenergy and biofuel have become very attractive due to the large diversity of resources available for such energies (Sharma et al. 2013; Quddus et al. 2018). Different categories of biomass feedstocks can be converted to bioenergy/or biofuel using different technologies (Yue et al. 2014; Ben Daya and Noureldath 2019). This study can be adapted to any biomass category and technology, producing bioenergies and biofuels.

Although using biomass has advantages in generating energy compared with fossil fuels, there are some barriers to its utilization. Such barriers include uncertainty and seasonality of available biomass in addition to its perishability (Rentizelas et al. 2009) that impact the performance of the bioenergy production process. Here we define biomass yield as the bioenergy and/or biofuel output over the amount of input biomass. Perishability is defined as a decrease in biomass yield over time. In other words it is a consequence of the *aging* of biomass in storage. The *perishability rate* (the speed at which perishability takes place) differs from one biomass to another. It happens mainly because of chemical reactions. Hence, we distinguish between the initial yield corresponding to that of fresh (zero age) biomass and the yield of "old" biomass at the beginning of each period. Again, this initial yield differs from one biomass to another.

This study proposes a multi-period production planning model for a biorefinery converting perishable biomass to bioenergy and biofuel under a dynamic demand. The objective is to maximize the profit of the biorefinery. The model optimizes the following decisions:

1. The quantity of purchased, stored, assigned, and converted biomass (into bioenergy or biofuel).
2. The amount of generated bioenergy and biofuel as well as the amount of stored biofuel.
3. The amount of bioenergy and biofuel to sell.

This model has two main features. First, controlling biomass perishability by monitoring the age of biomass. Second, storing energy in the form of non-perishable biofuel which can be kept in the warehouse and converted into bioenergy whenever required. The energy storage has two advantages: i) Matching the supply of bioenergy with the dynamic demand; ii) Tackling the issue of storage limitation of biomass due to perishability or storage capacity.

Effective management and planning of the biorefinery have a prominent impact on decreasing production costs and making biomass a valuable source of energy. Operations research and mathematical modeling can be used to accomplish that. Different models have been developed to optimize the production planning of the biorefineries (Cambero et al. 2015; Razm et al. 2019b; Uhlemair et al. 2014; Palak et al. 2014; Razm et al. 2021). However, the effect of biomass perishability is not effectively incorporated in most of these models. Storing energy is another challenge in production planning, because it is not economic on a large scale or not technically feasible. According to the European Commission (commission 2020), consumption of energy has to match its generation. This balance is essential to maintain a safe and stable supply of energy. Biofuel storage allows more flexibility on when to generate bioenergy and therefore helps to match energy supply with demand. In the literature related to the production planning of bioenergy from biomass, energy storage is rarely considered.

Accordingly, the contributions of this study are as follows:

1. Incorporating dynamic perishability of biomass into the production planning model.
2. Incorporating energy storage (through biofuel storage) into the production planning model to match supply with demand.
3. Monitoring the biomass age to manage biomass perishability and biorefinery profitability.
4. The proposed model can be easily applied to the real world. It can be highly practical for biorefineries with two main challenges-perishability and energy storage- and it can even turn the challenges into opportunities to obtain more profit and health benefits.

We develop the optimization model and conduct numerical experiments to derive managerial insights. Some of our results suggest that.

1. There is a threshold value on the perishability rate above which perishability does not have any longer impact on the profit. In this case, the manager should buy the less expensive biomass regardless of its perishability rate.
2. Energy storage under the form of biofuel results in considerable increase in profit and smoother production at the facility even when there is a high fluctuation in price and demand.
3. The decision maker could choose to impose a maximum age (maximum storage time) of the biomass to enhance quality and reduce health risks. In this case, the model provides guidelines for this choice with the least significant impact on profit.

The remainder of the article is structured as follows: a review of the relevant literature is given in Section 2. The problem definition is presented in Section 3. In Section 4, the model formulation is presented. The base case data is described in Section 5. We conduct our experiments in Section 6 and drive insights. In Section 7, we conclude and give future research directions.

2. Literature review

We can classify the relevant studies into three categories. First, the studies that focused on production planning of the pre-processing plants producing the processed biomass for other biorefineries. Second, the studies that focused on designing a new network for producing bioenergy and/or biofuel from biomass. Their goal is to find the locations of the biorefineries (the suppliers and distribution centers) (Rentizelas and Tatsiopoulou 2010). Third, the studies that focused on production planning of an existing biorefinery. There are few studies in the third category.

2.1. Production planning in the preprocessing plants

Eriksson and Björheden (1989) proposed a production planning model used for one preprocessing center to supply feedstocks for one biorefinery. The amount of biomass transported from different suppliers (forest regions), amount of stored biomass, and amount of chips production were the main decisions. However, the authors did not address the important features of the biomass like perishability and its effect on the output of the process.

Some studies considered the intermediate terminals where biomass quality (initial yield) is improved before delivering it to the biorefinery. Rentizelas et al. (2009) and Gautam et al. (2017) proposed production planning models for the intermediate terminals supplying the feedstocks for the existing biorefineries. The models determine the amount of biomass to chip, store, and transport. The intermediate terminal was used for preprocessing, handling, and storage of biomass for a long time. Nonetheless, according to Kanzian et al. (2009), storing biomass in the intermediate site leads to increasing the total costs of supplying biomass for the biorefineries, because of more transportation, loading, and unloading of the biomass.

According to Gunnarsson et al. (2004) the stored biomass feedstocks have to be protected against rain, and also

storing biomass feedstocks deteriorates the energy value of the biomass. Consequently, Gautam et al. (2017) considered two types of biomass storage at the intermediate terminals, storage under a shed and open-air storage. They assumed that the quality of the biomass feedstocks was more affected in the open-air storage. Unlike Kanzian et al. (2009), Gautam et al. (2017) highlighted that intermediate terminals have advantages in terms of reducing the costs of supplying biomass for the biorefinery. They asserted that the intermediate terminal, using storage of biomass under shed (comparing with open-air storage), leads to more control on the quality of biomass. Therefore, the costs may be saved because of the biomass quality improvement. Although these studies considered quality of biomass, they focused on the decisions related to supplying biomass for other biorefineries rather than bioenergy production in the biorefinery. In other words, they focused on the flow of biomass feedstocks to the gate of the biorefineries.

2.2. Network desing in biorefineies

A GIS (Geographic Information System) approach combined with a Mixed Integer Non-Linear Programming (MINLP) model was developed by Santibañez-Aguilar et al. (2019) for production planning of several biorefineries. Different agricultural biomass was used for biofuel and bioenergy production. The amount of biomass acquisition in one year, the amount of biofuel and bioenergy production, and the amount of storing and selling biofuel were determined in the production planning model. In this study, biomass quality and biomass storage were not considered, although the authors used the perishable biomass which is available at specific season.

Some studies considered a deterioration rate as biomass waste, and some others did not consider storage to prevent this biomass deterioration. Bairamzadeh et al. (2018) proposed a production planning model for different biorefineries using agricultural biomass feedstocks. Unlike the former model (Santibañez-Aguilar et al. (2019)), Bairamzadeh et al. (2018) considered biomass storage and biomass deterioration. They used a constant parameter (in the inventory constraint) as the deterioration rate of biomass in each period in the warehouse. It means that a percentage of the stored biomass is thrown away from the warehouse each month. Cambero et al. (2015) proposed an optimization model to generate bioenergy and biofuel from forest residues. The production planning was defined for several biorefineries. The model optimized the decisions such as the amount of purchased and assigned biomass, the amount of bioenergy and biofuel production, and the amount of biofuel storage. Non-merchantable logs, harvesting residues, wood chips, hog fuel, shavings, and sawdust were considered the biomass feedstocks. They announced that in order to prevent the deterioration of biomass, biomass storage is not considered in the study.

Note that biomass quality (different initial yield) and production planning are the links among three mentioned categories (Subsections 2.1, 2.2, and 2.3).

Miret et al. (2016) and Zhang et al. (2016) also considered biomass deterioration in their models. Their production planning models involved storage biomass to generate bioethanol. One year is considered as the length of the planning

horizon and each month as one period. They considered a constant biomass deterioration rate during the storage. A percentage of stored biomass is considered as waste in each period.

The form of collecting biomass could affect the deterioration rate of the biomass and the costs of the production planning. Three forms of collecting switchgrass such as loose chop, square bales, and round bales were considered by Zhang et al. (2013). The loose chop was sent to the intermediate facilities for densification. Two other collecting forms of biomass, the square and round bales, could be stored at the farms (the biomass supply sites). Then, they directly are sent to the biorefineries. Although the loose chop created more transportation costs (not directly sent to the biorefineries), the model chooses the loose chop as the best harvesting way. They asserted that after preprocessing (creating more density), the dry matter loss decreases. In the same way, two forms of collecting biomass were considered by Larson et al. (2015). They suggested the collection of biomass in the form of square bales is better, because it efficiently occupies the space of the warehouse, and also it is easier for transportation. Therefore, the square bale form was considered as more economical in their research, although they announced that the square bale form has more dry matter losses comparing with the round bale.

Two studies, Castillo-Villar et al. (2017), Nur et al. (2021), incorporated the quality-related costs into a two-stage stochastic model. The quality costs impacted the decisions made in production planning. They considered biomass with different characteristics (moisture and ash content) coming from the suppliers (with different deterioration rates). Nur et al. (2021) suggested densification and preprocessing of biomass in the depots before converting the biomass into biofuel. They asserted densification and preprocessing of biomass can impact the biomass conversion process as well as the biomass transportation cost. They considered the distance between the suppliers and biorefineries to reduce the biomass quality loss over time. The amount of the purchased, stored, used biomass, and amount of the bioethanol production are the main decisions in the production planning model of this study.

In the literature related to bioenergy/biofuel production, the perishability of biomass was not very well applied into the production planning models. Most relevant works only considered a constant deterioration rate in the inventory constraint. It means that each period a percentage of the biomass is thrown away as waste. Nonetheless, the biomass perishability can affect the amount of biofuel obtained from the conversion process (Fuller 1985), and also the amount of bioenergy obtained from the conversion process (yield of biomass conversion) (Shabani and Sowlati 2013).

2.3. Production planning in existing biorefineries

Shabani and Sowlati (2013), proposed an optimization model to maximize the total profit of an existing biorefinery. Forest residues were considered as input biomass. One-year production planning with monthly periods was considered. The model involves procurement of biomass, storage, power production, and ash management (extra costs for removing ash after combustion process). The effect of biomass quality on the amount of generated electricity was considered in

the model. In the power production constraint, they considered a static parameter (Quality Reduction Factor only at the specific conditions) that is multiplied by a binary variable and the variable of consumed biomass. They linked the binary variable to biomass storage. They assumed that the binary variable is equal to one if the storage level is lower than the storage lower limit in one period. It means that the biomass is kept in the smaller pile. This causes generating insufficient internal heat in the pile, so the quality reduction occurs (low temperature and wet environment).

However, according to Fuller (1985) the deterioration of biomass is a complex process that depends on many factors, and it does not happen only in the low temperature. The chemical reactions continuously occur and lead to losses of the valuable materials in the biomass over storage time.

In terms of energy storage, some studies introduced different methods and technologies to store energy. For instance: 1) using different kinds of battery (e.g., flow battery, lithium battery) (Kousksou et al. 2014; Wichmann et al. 2019); 2) using the compressed air storage system (He et al. 2021); 3) using thermochemical energy storage system (Wu et al. 2021); 4) using superconducting magnetic energy storage (Diezmartínez 2021). Some studies introduced biofuel as one way to store energy (Ma 2021). In contrast, to the best of our knowledge, no previous study considered biofuel as a way of storing energy in the production planning model for converting biomass-to-bioenergy and/or biofuel.

Table 1 shows the results of the literature review related to the bioenergy and/or biofuel production planning models considering biomass quality. In Table 1, the generic type of feedstock means using more than one type of biomass (e.g. forest residues and agricultural biomass). Monitoring the age of biomass means controlling the time length of storing fresh biomass. Biomass loss means throwing biomass away from the warehouse as waste. Static quality reduction means reducing (not continuously) the biomass quality (the valuable materials) only at specific conditions (e.g. low temperature). Dynamic quality reduction means reducing (continuously) the biomass quality based on biomass aging. Energy storage in the form of biofuel means storing the biofuel which will be converted into bioenergy inside the biorefinery later. Of course, other papers considered biofuel storage, but our main interest here is in the conversion of biofuel into bioenergy inside the biorefinery and the integration of this decision into the biorefinery production planning model. The yield of biomass conversion impacted by biomass quality means changing the amount of output by changing the quality of input (biomass). The planning horizon is divided into three columns: i) continuous-time horizon; ii) discrete-time horizon (e.g., one year with weekly periods); iii) single period. Both the continuous and discrete-time horizons are multi-period.

As shown in Table 1, there is a research gap in production planning for a biorefinery using perishable biomass. The perishability of biomass and energy storage need to be incorporated in the production planning models. This study tries to fill this gap.

In this paper, one existing biorefinery is considered. We consider a planning horizon of 1 year divided into time

periods, one period is equal to one month. We consider a dynamic biomass quality reduction (based on the age of biomass) over storage time and this impacts the yield of the biomass conversion. It means that the yield of biomass conversion is dynamically reduced over time, because perishability is a dynamic process. Note that the applicability of our model is general, and it can also be applied for two other cases (the static quality reduction and the biomass loss (Shabani and Sowlati 2013; Razm et al. 2019a; Bairamzadeh et al. 2018)). Moreover, in this study, biofuel is considered as a method to store energy that can be converted to bioenergy later inside the biorefinery.

Table 1

The literature related to the production planning vs. this study

Article	Feedstock	Inventory planning			Perishability (in the stor-age)			Conversion technology			Energy storage	The yield of biomass conversion	Planning horizon		
	Specific/Generic	Biomass storage	Monitoring the biomass age	Biofuel storage	Biomass loss	Static quality reduction	Dynamic quality reduction	Biomass preprocessing	Biomass to biofuel	Biomass to bioenergy	In the form of biofuel	Impacted by biomass quality	Continuous (multi-period)	Discrete (multi-period)	Single-period
Eriksson and Björheden (1989)	S	X						X					X		
Gunnarsson et al. (2004)	S	X						X						X	
Kanzian et al. (2009)	S	X						X						X	
Zhang et al. (2013)	S	X			X			X	X					X	
Larson et al. (2015)	S	X			X				X					X	
Shabani and Sowlati (2013)	S	X				X				X		X		X	
Akhtari et al. (2014)	S	X						X						X	
Dansereau et al. (2014)	S	X						X	X	X		X		X	
Cambero et al. (2015)	S			X				X	X					X	
Miret et al. (2016)	G	X		X	X			X	X					X	
Zhang et al. (2016)	S	X			X			X	X					X	
Gautam et al. (2017)	S	X						X						X	
Castillo-Villar et al. (2017)	S								X					X	
Bairamzadeh et al. (2018)	S	X		X	X				X					X	
Santibañez-Aguilar et al. (2019)	G			X					X	X					X
Nur et al. (2021)	G	X			X			X	X			X		X	
Proposed model	G	X	X	X	X	X	X		X	X	X	X		X	

3. Problem definition

The general structure of a bioenergy production system is shown in Figure 1. In one biorefinery, there are usually some conversion technologies (Cheng and Anderson 2017) and warehouses as shown in Figure 1. In this Figure, B is a type of biomass (as feedstock), and A is the age of biomass. T represents periods, F shows biofuel, and E means bioenergy. In this study, the subscripts represent the indices (not superscripts). The superscript in the notation is only used for more description of the notation (e.g., in E_t^B , B is not an index). Only one biorefinery is considered in the example of bioenergy production system, although more than one biorefinery can be also used.

Different kinds of fresh biomass (e.g., crop-based biomass, agricultural wastes, forest residues, etc.) are brought to the biorefinery ($X_{b,0,t}$). The biomass, the perishable product, is stored in the biomass warehouse ($I_{b,a,t}^B$). The more time for storing biomass, the more age it has. The more age, the more perishability. Thus, the quality of the biomass will change. The biomass quality can impact the biomass conversion process.

In the next stage, the biomass is assigned to two types of conversion technology. The first type of technology converts the biomass ($X_{b,a,t}^F$) to the biofuel such as bioethanol, biodiesel, pellet. The second one converts the biomass ($X_{b,a,t}^E$) to the bioenergy such as heat and electricity. The heat or electricity made from biomass is immediately sold after generating (E_t^B). However, the generated biofuel (F_t) is stored in the biofuel warehouse. The stored biofuel (I_t^F) can be sold as biofuel or bioenergy (as stored energy). It means there are two ways for selling the stored biofuel. First, biofuel can be directly sold to the customer as biofuel (F_t^C). Second, biofuel can be assigned to the technology (F_t^E) to convert to bioenergy, then the bioenergy generated from the biofuel (E_t^F) will be sold to the customer. Consequently, in the second way, the biofuel can be stored in the biofuel storage for a long time. so the bioenergy generated by burning this stored biofuel is also stored for a long time.

Unlike the basic bioenergy production systems (without energy storage), our bioenergy production system (with energy storage) can store bioenergy for a long time. Energy storage is one of the challenges that the basic bioenergy production systems (without energy storage) are facing with. In planning for the biorefinery production, when consumption of energy does not match the generation of that (because of fluctuation in demand, price, available biomass, etc.), the energy storage can make the required balance for smoother production to provide a safe and stable supply of energy (commission 2020).

In terms of the energy storage application, the difference between the basic bioenergy production systems (without energy storage) and the proposed bioenergy production system (with energy storage) is shown by the red ellipse in Figure 1, and it can be easily applied to the basic bioenergy production systems (without energy storage).

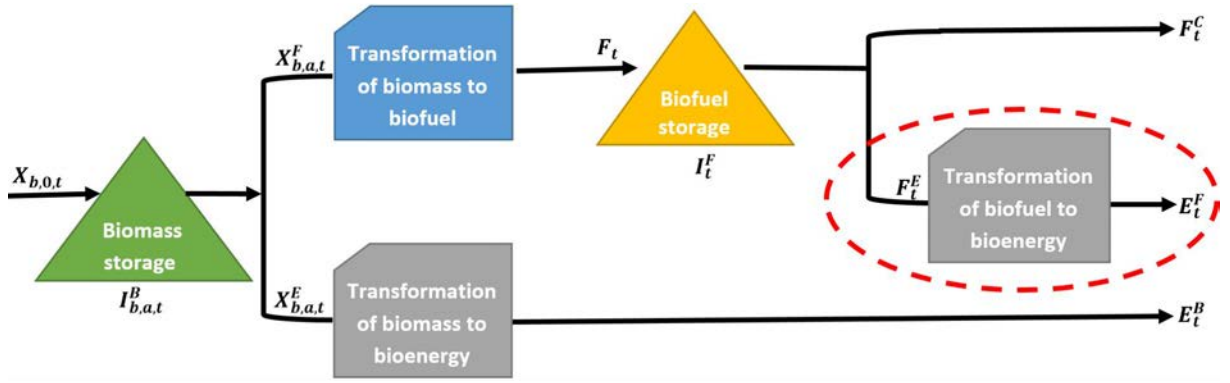


Figure 1: Illustrative figure of the bioenergy production system.

4. Model formulation:

In this study, a multi-period linear programming mathematical model is developed for the optimal planning and operation of the bioenergy production systems. Before formulating the problem, the verbal description of the bioenergy production system is presented to better understand the mathematical model:

$$\begin{aligned} \text{Maximize profit} = & \quad [\text{Biofuel revenue} + \text{Bioenergy revenue}] \\ & - [\text{Biomass costs} + \text{Production costs} + \text{Inventory costs}] \end{aligned}$$

Subject to :

- Biomass availability constraints
- Biomass inventory balance equations
- Biofuel inventory balance equations
- Demand constraints
- Production (conversion) equations

Table 2 presents the notations which will be used in the mathematical model.

4.1. Objective function:

The objective function (14) in the proposed model maximizes the total profit (the total revenues minus total costs). The total revenues include the revenues obtained from: 1) selling biofuel directly to the customer; 2) selling bioenergy that is generated from biomass; 3) selling bioenergy that is generated from biofuel. The total costs include the costs enforced by: 1) purchasing the fresh biomass; 2) converting biomass to biofuel (production costs); 3) converting biomass to bioenergy; 4) converting biofuel to bioenergy; 5) the inventory holding of biomass; and 6) the inventory

holding of biofuel.

$$\begin{aligned} \text{Maximize } & \sum_t (p^F \cdot F_t^C + p^E (E_t^B + E_t^F)) - \sum_b \sum_a \sum_t (c_{b,t}^B \cdot X_{b,a,t} + c_{b,t}^{BF} X_{b,a,t}^F + c_{b,t}^{BE} X_{b,a,t}^E) \\ & - \sum_t c_t^{FE} \cdot F_t^E - \sum_b \sum_a \sum_t h_{b,t}^B \cdot I_{b,a,t}^B - \sum_t h_t^F \cdot I_t^F \end{aligned} \quad (1)$$

4.2. Constraints:

Constraints (2) ensure that amount of the biomass b with age $a=0$ (fresh biomass) coming from the suppliers could not be more than the available biomass in each period.

$$X_{b,0,t} \leq \omega_{b,t} \quad \forall b, t \quad (2)$$

Constraints (3) and (4) ensure the mass balances of biomass feedstocks (the fresh or aged biomass) in each period. In constraints (3), the amount of the fresh biomass coming from suppliers (i.e. $X_{b,a=0,t}$) are equal to the amount of the fresh biomass inventory (i.e. $I_{b,a=0,t}^B$), plus the amount of fresh biomass assigned to the biofuel technology (i.e. $X_{b,a=0,t}^F$), plus the amount of fresh biomass assigned to the bioenergy technology (i.e. $X_{b,a,t}^E$). Constraints (3) are corresponding to the fresh biomass ($a = 0$).

Constraints (4) ensure that the inventory of each type of biomass with age $a-1$ at the end of period $t-1$ (i.e. $I_{b,a-1,t-1}^B$) has to be equal to the inventory of old biomass with age a at the end of the period t (i.e. $I_{b,a,t}^B$), plus the amount of old biomass assigned to the biofuel technology (i.e. $X_{b,a,t}^F$), plus the amount of old biomass assigned to the bioenergy technology (i.e. $X_{b,a,t}^E$). Constraints (4) are corresponding to the old biomass ($a \in A \setminus \{0\}$).

$$X_{b,0,t} = I_{b,0,t}^B + X_{b,0,t}^F + X_{b,0,t}^E \quad a = 0, \forall b, t \quad (3)$$

$$I_{b,a-1,t-1}^B = I_{b,a,t}^B + X_{b,a,t}^F + X_{b,a,t}^E \quad \forall b, t, a \in A \setminus \{0\} \quad (4)$$

Constraints (5) ensure that the amount of biofuel generated by biofuel technology (i.e. F_t), plus the biofuel inventory at the end of period $t-1$ (i.e. I_{t-1}^F) have to be equal to the biofuel inventory at the end of the period t (i.e. I_t^F), plus the amount of biofuel that is directly sold to the customer (i.e. F_t^C), plus the amount of biofuel assigned to the technology to generate bioenergy (i.e. F_t^E).

$$I_{t-1}^F + F_t = I_t^F + F_t^C + F_t^E \quad \forall b, t \quad (5)$$

Constraints (6) and (7) show the maximum demand limitations for biofuel and bioenergy. The demand for bioenergy could be satisfied by the bioenergy obtained from biomass, and/or by the bioenergy obtained from biofuel.

$$F_t^C \leq D_t^{Fmax} \quad \forall t \quad (6)$$

$$E_t^F + E_t^B \leq D_t^{Emax} \quad \forall t \quad (7)$$

Constraints (8) guarantee that the amount of biofuel produced by the technology is equal to the amount of biomass multiplied by the conversion efficiency (production yields) concerning the biomass quality whether is fresh ($a=0$) or old ($a \neq 0$).

$$\sum_b \sum_a \alpha_{b,a}^F \cdot X_{b,a,t}^F = F_t \quad \forall t \quad (8)$$

Constraints (9) guarantee that the amount of bioenergy produced by the technology is equal to the amount of biomass multiplied by the conversion efficiency (production yields) considering the fresh biomass ($a=0$) or old biomass ($a \neq 0$). Constraints (8) and (9) represent the conversion of biomass which is perishable.

$$\sum_b \sum_a \alpha_{b,a}^E \cdot X_{b,a,t}^E = E_t^B \quad \forall t \quad (9)$$

Constraints (10) are related to the conversion efficiency (production yields) of the process of generating bioenergy from biofuel.

$$\eta^{FE} \cdot F_t^E = E_t^F \quad \forall t \quad (10)$$

Constraints (11), are non-negativity constraints of the model.

$$X_{b,a,t}, X_{b,a,t}^F, X_{b,a,t}^E, F_t, F_t^C, F_t^E, E_t^F, E_t^B, I_t^F, I_{b,a,t}^B \geq 0 \quad \forall b, a, t \quad (11)$$

4.3. Note on the yield and perishability rate

When a new lot of the biomass arrives to the warehouse, it is considered as fresh with an age $a = 0$. As the biomass is carried into inventory, its age increases and its yield α_{ba}^F decreases based on the following formula (equation (12)),

$$\alpha_{ba}^F = \alpha_{b,0}^F \times (1 - a \times \xi\%) \quad (12)$$

where ξ shows the perishability rate of the biomass and a its age.

For example, the yield of the fresh corn stover (the biomass of type $b = 1$) is $\alpha_{1,0}^F = 0.272$ (?). If we assume that perishability rate is 5%, i.e. the yield decreases by 5% each month, the yield of corn stover (m^3/t) after one month becomes $\alpha_{1,1}^F = 0.2584$. Similarly we can get $\alpha_{1,2}^F = 0.2448$, $\alpha_{1,3}^F = 0.2312$, and $\alpha_{1,11}^F = 0.1224$. Notice that if $\xi \geq 50\%$, the biomass cannot be stored more than one period of time. Hence, in this case, $\alpha_{ba}^F = 0, \forall a \geq 2$.

5. Base case data

The proposed model was applied to a base case with data compiled from different sources. Five kinds of biomass are considered: corn stover, wheat straw, switchgrass, forest residues, and sawmill wastes. The availability of the different types of biomass varies over the year and from one region to another. There were attempts to estimate such availability (e.g. bioenergyeurope 2020). For instance, Figure 2 shows biomass availability in a given country. We used this data of biomass availability, knowing that our model is generic and can be applied to other distributions.

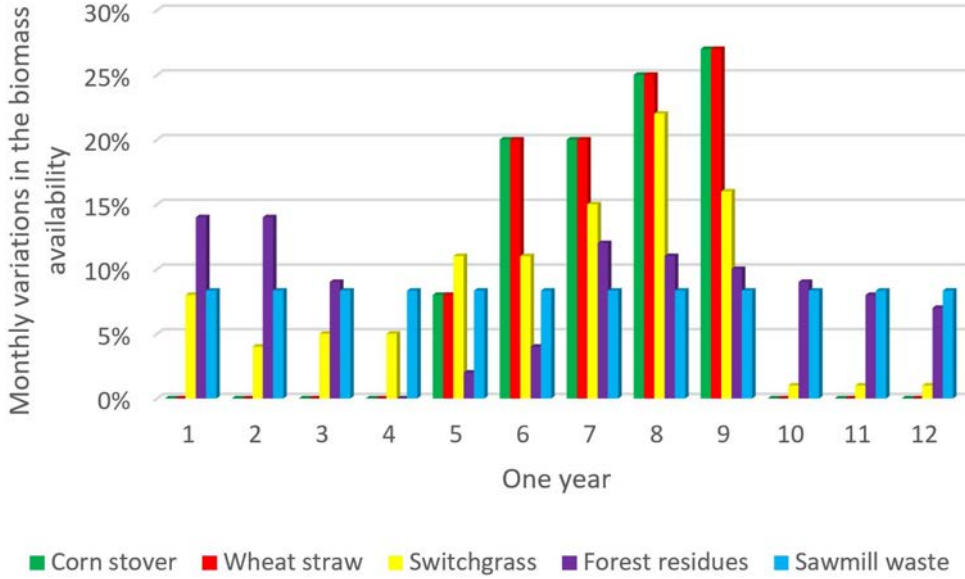


Figure 2: Biomass availability

Other important biomass characteristics such as moisture content, energy content, and purchase prices are presented in Table 13 in Appendix A. In this study, it is supposed that the bioethanol (as biofuel) generated from the different biomass can also be used as input for generating the bioenergy. The associated energy content and corresponding references are shown in Appendix A. In the base case, we consider one year as the basic planning horizon with 12 monthly periods. Then, in Section 6.6, we extend it to three years with 36 monthly periods.

In the biorefinery, there are two kinds of technology. First, using a biochemical conversion process (Fermentation technology), the biorefinery converts corn stover, wheat straw, and switchgrass to bioethanol. Second, the thermochemical conversion process (Combustion technology) is used. Forest residues, sawmill waste, and bioethanol can be

used as input feedstocks to be burnt to generate bioenergy. The assigned technology, the the facility cost, and the yield of the fresh biomass when it is converted by the different technologies are given in Appendix B, in Table 14 and 16.

The yields in Table 14 can vary with the change of the biomass quality. It is worth noting that the yield of the bioenergy can also be obtained by (13) (Akhtari et al. 2018, Kenney et al. 2013, Nur et al. 2021). It indicates that the yield in Megawatt-hour per tonne (MWh/t) is a function of the energy content in Gigajoule per tonne (GJ/t), the coefficient of technology efficiency and a constant of 3.6 to convert GJ to MWh (1MWh = 3.6 GJ). Note that the values of "energy content" in Table 13 are used as inputs for (13), and then, the results are shown in Table 14 as inputs for the model.

$$\text{Bioenergy product Yield} \left(\frac{\text{MWh}}{t} \right) = \frac{\text{Energy content} \left(\frac{\text{GJ}}{t} \right) \times \text{Efficiency of bioenergy technology}}{3.6 \left(\frac{\text{GJ}}{\text{MWh}} \right)} \quad (13)$$

Two final products are considered in this study; Bioethanol as biofuel, and electricity as bioenergy. In addition, bioethanol can also be used as input feedstock to be burnt for generating electricity. The price of selling each cubic meter (m^3) of biofuel, the price of selling each Megawatt hour (MWh) of bioenergy, the holding cost of each tonne of biomass, and the holding cost of each cubic meter of bifouel are shown in Table 15 (Appendix C).

In the base case, we suppose that the holding costs (for biomass and biofuel) are fixed in each period. The annual maximum demand is supposed to be 7194050 MWh for bioenergy, and to be 118657642 m^3 for biofuel (Iran, exports included) (NIOPDC 2014; Energy 2017)). The demand for products can vary in each period (e.g. NIOPDC 2014; bioenergyeurope 2020; Energy 2017). Table 17 shows the fluctuation of demand in each month. The planning horizon is considered one year with 12 monthly periods. Note that in Section 6.6, we change some of these assumptions for further analysis.

6. Numerical Experiments

The proposed model was coded in GAMS 24.1.2 and solved using CPLEX solver (version 20.1). The model was implemented on an Intel Core i7, 2.11 GHz processor with 32 GB of RAM. We conduct a numerical analysis to derive a series of insights into the optimization of operations and profitability of the biorefinery. The results are presented in this section as follows: 1) the optimal solution of the base case is described in Subsection 6.1; 2) the biomass perishability is analyzed in Subsection 6.2; 3) the maximum age of biomass and the restrictions of storing perishable biomass are discussed in Subsection 6.3; 4) the interest of storing biofuel to transform it later to bioenergy is discussed in Subsection 6.4; 5) a sensitivity analysis is performed in Subsection 6.5; 6) finally, in Section 6.6, we consider some of new assumptions and run the model for further analysis.

6.1. Optimal solution of the base case

In this this part, we use the base case data explained in Section 5, and set the value of the perishability rate (see equation (12)) to 5%. Then, the model was run. Tables 3 and 8 show the optimal solution. In Table 3, the column named the fresh stored biomass shows summation of the stored biomass with age equal to zero ($a = 0$) in all periods. The column that is named the old stored biomass shows summation of the stored bioamss with age more than one ($a \geq 1$) in all periods. Table 3 also shows the optimal profit and the total corresponding revenue and cost over the planning horizon. Note that we consider one year as the basic planning horizon with 12 monthly periods in the base case, and we extend it in Section 6.6. Table 8 shows the optimal biomass storage over the planning horizon in more details. For example, 2899 tonne of biomass type 5 with age 6 is stored in period 7. The total biomass type 5 with age 6 over the planning horizon is equal to 5798 tonne. Theses results are shown in last row of Table 8. Therefore, the proposed model helps to manage biomass perishability by monitoring the age of biomass over the planning horizon.

Table 2

Decision variables, parameters, and sets of the model

Symbol	Definition
B	Set of biomass feedstock types; index $b \in B$
A	Set of biomass age; index $a \in A$
T	Set of periods; index $t \in T$
Parameter	
p^F	Biofuel selling price (\$/unit of product)
p^E	Bioenergy selling price (\$/MWh)
$c_{b,t}^B$	Cost of purchasing <i>fresh</i> biomass b in period t (\$/t)
$c_{b,t}^{BF}$	Cost of converting biomass b to biofuel in period t (\$/t)
$c_{b,t}^{BE}$	Cost of converting biomass b to bioenergy during period t (\$/t)
c_t^{FE}	Cost of converting biofuel to bioenergy during period t (\$/unit of product)
$S_{b,t}^F$	Fixed cost (setup cost) related to the conversion facility generating biofuel from biomass b in period t
$S_{b,t}^E$	Fixed cost (setup cost) related to the conversion facility generating bioenergy from biomass b in period t
S^{FE}	Fixed cost (setup cost) related to the conversion facility generating bioenergy from biofuel in period t
$\Psi_{b,t}^F$	Maximum capacity of the conversion facility generating biofuel from biomass b in period t (input product/each period)
$\Psi_{b,t}^E$	Maximum capacity of the conversion facility generating bioenergy from biomass b in period t (input product/each period)
Ψ_t^{FE}	Maximum capacity of the conversion facility generating bioenergy from biofuel in period t (input product/each period)
$h_{b,t}^B$	Cost of holding biomass b in period t (\$/t)
h_t^F	Cost of holding biofuel in period t (\$/unit of product)
$\omega_{b,t}$	Available biomass b at the supply sites in period t (tonne)
$\alpha_{b,a}^F$	The yield of biofuel when using the biomass with age a (unit of product output/tonne of biomass input).
$\alpha_{b,a}^E$	The yield of bioenergy when using the biomass with age a (unit of product output/tonne of biomass input).
η^{FE}	The yield of bioenergy when using the biofuel (unit of product output/ unit of product input)
D_t^{Fmax}	Maximum demand for biofuel (unit of product)
D_t^{Emax}	Maximum demand for bioenergy (MWh)
Decision variable	
F_t	The total amount of biofuel produced in period t (unit of product)
F_t^C	Amount of biofuel sent directly to the customers in period t (unit of product)
F_t^E	Amount of biofuel used as input for the technology converting biofuel to bioenergy in period t (unit of product)
E_t^F	Amount of bioenergy obtained from converting biofuel (MWh)
E_t^B	Amount of bioenergy obtained from converting biomass (MWh)
$X_{b,a,t}$	Amount of purchased biomass b with age a in period t (t)
$X_{b,a,t}^F$	Amount of biomass b with age a that is used as input for biofuel technology in period t (t)
$X_{b,a,t}^E$	Amount of biomass b with age a that is used as input for bioenergy technology in period t (t)
$I_{b,a,t}^B$	Amount of biomass b with age a stored in the biomass storage in period t (t)
I_t^F	Amount of biofuel stored in the biofuel storage in period t (unit of product).
$Y_{b,t}^F$	Binary variable: 1, if the conversion facility generating biofuel from biomass b is activated in period t ; 0, otherwise
$Y_{b,t}^E$	Binary variable: 1, if the conversion facility generating bioenergy from biomass b is activated in period t ; 0, otherwise
$Y_{b,t}^{FE}$	Binary variable: 1, if the conversion facility generating bioenergy from biofuel is activated in period t ; 0, otherwise

Table 3

Decomposition of the optimal solution value for the base case

Profit (\$)	Revenue (\$)	Costs (\$)	The fresh stored biomass (t)	The old stored biomass (t)
$2.32E + 08$	$8.89E + 08$	$6.57E + 08$	553883	1977693

Table 4
Amounts of inventory with different ages over one year

Biomass Type		T												Total inventory of age a
Age	Storage	1	2	3	4	5	6	7	8	9	10	11	12	
$b = 4$	$a = 0$	$I^B_{b=4,a=0,t}$	116200	116200	116200	-	-	99600	91300	-	-	-	-	539500
	$a = 1$	$I^B_{b=4,a=1,t}$	-	116200	116200	116200	-	-	99600	-	-	-	-	448200
	$a = 2$	$I^B_{b=4,a=2,t}$	-	-	107309	116200	116200	-	-	-	-	-	-	339709
	$a = 3$	$I^B_{b=4,a=3,t}$	-	-	-	95249	116200	116200	-	-	-	-	-	327649
	$a = 4$	$I^B_{b=4,a=4,t}$	-	-	-	-	82435	116200	116200	-	-	-	-	314835
	$a = 5$	$I^B_{b=4,a=5,t}$	-	-	-	-	-	68767	116200	116200	-	-	-	301167
	$a = 6$	$I^B_{b=4,a=6,t}$	-	-	-	-	-	-	54122	116200	-	-	-	170322
$a = 7$	$I^B_{b=4,a=7,t}$	-	-	-	-	-	-	-	38352	-	-	-	38352	
$b = 5$	$a = 0$	$I^B_{b=5,a=0,t}$	2787	2899	2899	-	-	2899	2899	-	-	-	-	11484
	$a = 1$	$I^B_{b=5,a=1,t}$	-	2669	2899	2899	-	-	2899	-	-	-	-	11366
	$a = 2$	$I^B_{b=5,a=2,t}$	-	-	-	2899	2899	-	-	-	-	-	-	5798
	$a = 3$	$I^B_{b=5,a=3,t}$	-	-	-	-	2899	2899	-	-	-	-	-	5798
	$a = 4$	$I^B_{b=5,a=4,t}$	-	-	-	-	-	2899	2899	-	-	-	-	5798
	$a = 5$	$I^B_{b=5,a=5,t}$	-	-	-	-	-	-	2899	2899	-	-	-	5798
	$a = 6$	$I^B_{b=5,a=6,t}$	-	-	-	-	-	-	-	2899	2899	-	-	5798

6.2. The effects of biomass perishability

The effects of perishability on the total profit and the biomass storage are shown in Figure 3. Here, using equation (12), the rate of perishability (ξ) has been changed in the interval [0%-100%]. When the rate of perishability is increased to 50%, the total profit decreases by about 12%. After the threshold point of 50% perishability rate, the profit remains constant.

The initial assumption in this study is that the purchasing price of biomass ($c_{b,t}^B$) is independent of ξ . Buying biomass with low perishability rate, gives more flexibility to the manager to store this biomass over longer time periods without big losses in the yield. If the perishability rate is larger than 50%, the biomass can be stored at most for one period before its yield becomes zero. The yield in the second period of the stored biomass decreases as the perishability rate increases. The best solution in this case consists in avoiding storage of biomass at all, which results in the same profit for ξ values between 50% and 100%. Maximum period for storing the biomass will be discussed in more details in section 6.2.

In Figure 4, we carry the same analysis but we assume the price of the biomass is a function of its perishability rate, which is more realistic. In this case the purchasing price ($c_{b,t}^B$) is decreasing when ξ is increasing in [0%, 100%]. For the purpose of this experiment, $c_{b,t}^B$ will decrease with 1% for each 5% increase in the perishability rate in the interval $\xi \in [0\%, 100\%]$.

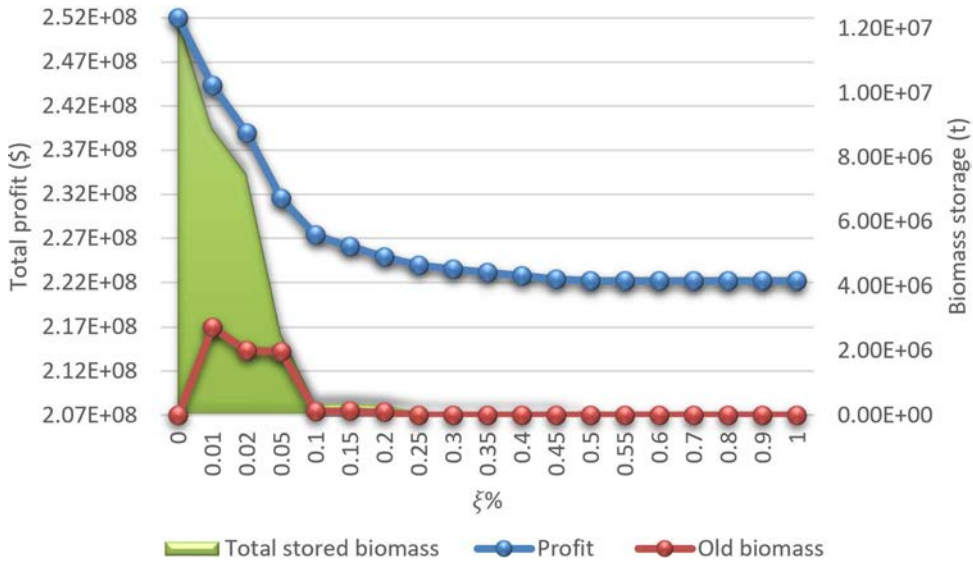


Figure 3: Effect of biomass perishability rate on profit and amount of stored biomass.

While, one could expect that manager prefers biomass with lower perishability rates as it provides him/her with higher flexibility, the results on Figure 4 show something quite different. When the biomass price is not constant, there is a trade-off between savings on the raw material cost and storage flexibility. Figure 4 shows that the total profit

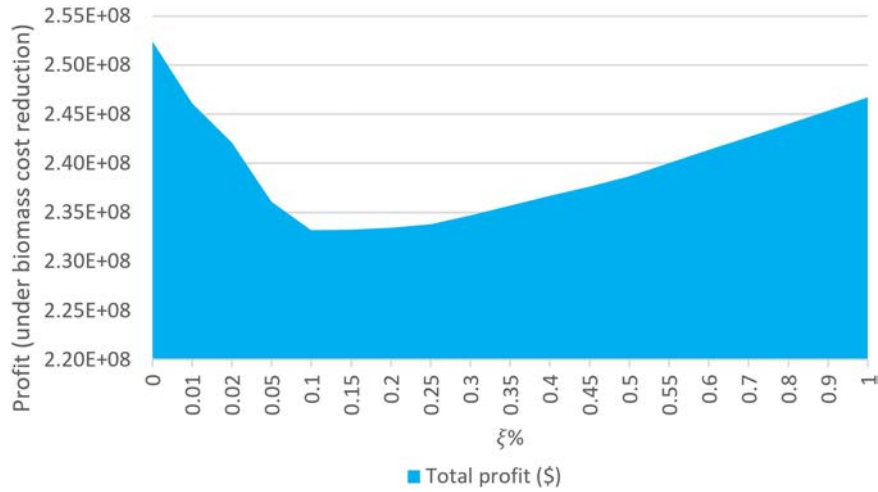


Figure 4: Effect of biomass perishability on the total profit: Biomass price decreases with 1% for each 5% increase in ξ .

increases for the values of ξ above 10%. In the range from 10% to 45% the amount of stored biomass is very low compared with $\xi = 0\%$. In this case, the price of biomass has more impact on the profit than the perishability rate. In the range [50%, 100%], the biorefinery does not stock any biomass to avoid perishability. However, it still takes advantage of the lower prices of such high perishability biomass.

6.3. The effects of the maximum age of biomass

The perishability rate is an indicator of the maximum amount of time biomass can be stored before its yield becomes zero. However, in practice, the manager should have the flexibility to decide on the maximum amount of time to store the biomass even if it still has a positive yield. For example, the manager might be concerned about health and safety problems made by storing the perishable biomass for long time, such as fungal (fungus) /spore formation (Rentizelas et al. 2009), or spontaneous ignition (Torrent et al. 2015) due to exothermic microbial degradation. Hence, the maximum age of biomass, here, means that the maximum number of time periods that biomass is allowed to be stored in a warehouse.

We analyze the effects of the maximum age of the biomass using the default value of perishability rate ($\xi = 5\%$). In this experiment, we decrease the maximum allowed age of the biomass from 11 to 0 time periods. Figure 5 shows the results of the tests. In each maximum age of biomass, we consider the summation of all old/fresh biomass that are stored in different periods.

The main insights from Figure 5 can be summarized in the following three points. First, when the maximum age of biomass increases from 0 to 2 periods, the profit significantly increases. This means that considering biomass storage is so important for managers, because they can significantly increase their profit compared with the case in which the maximum age is set to 0 that storage is not allowed for neither old biomass nor fresh biomass. Second, the curve is

almost flat on ranges [2, 5] and [8, 11]. The profit stays almost constant. In this case, the decision maker might prefer to set the maximum to the lowest value

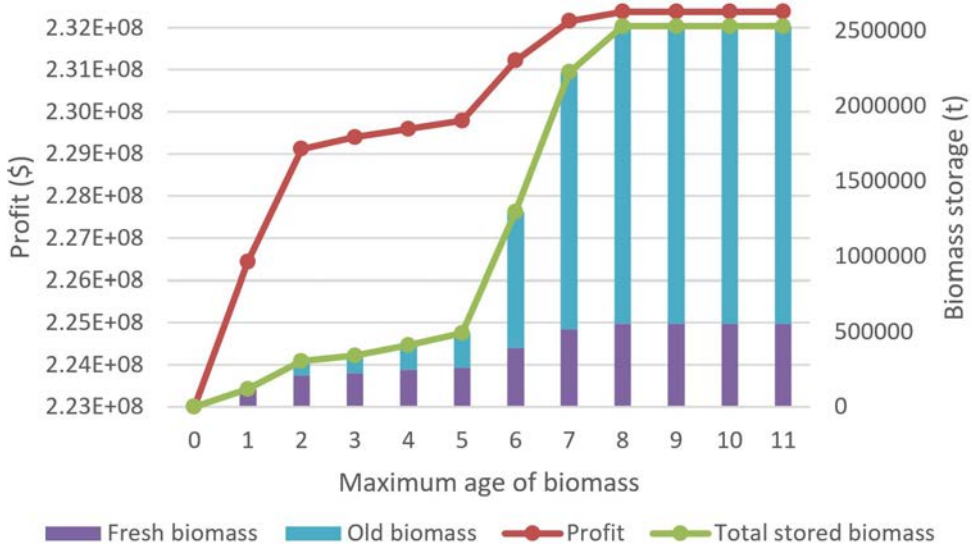


Figure 5: Maximum age of biomass

of the range (2 or 8) considering that the small loss in profit (between 2 and 5 periods maximum age) is offset by the health benefits incurred. Third, in the range from 5 to 8, we show a trade-off between the extra costs for longer time storage (perishable biomass) and the profit, so the manager can use this trade-off to determine the best maximum age. As a last note, beyond a certain value (here 8 periods), the total profit remains unchanged. This threshold value depends mostly on the inventory holding costs.

6.4. The value of energy storage

This part shows the advantages of energy storage application in the bioenergy production system, and compares the proposed model (with energy storage) with the existing models. Our model considers two types of outputs (bioenergy and biofuel). Unlike bioenergy, biofuel can be stored. We call this Energy Storage, because (unlike the existing models) it can be converted to bioenergy later inside the biorefinery. Therefore, biofuel storage can be used to match supply with demand. Inventory plays an important role in our model since it may be interesting to transform a large quantity of biomass to avoid perishability which is possible only when the output product can be stored since, otherwise, production will be lost.

Although the existing models in the literature considered biofuel storage, they did not convert the stored biofuel into the bioenergy inside the biorefinery. They sell biofuel directly to the customers. This part of converting stored biofuel (energy storage) to bioenergy is shown by a red ellipse in Figure 1. Now, we remove this part from our model (with energy storage) to obtain a basic model without energy storage. If we set the value of η^{FE} to 0 in constraint (10),

Table 5Optimal solution of the bioenergy production system ($\times 10^7$)

	Basic model (without energy storage)	Our model (with energy storage)
Profit (\$)	22.70	23.19
Biofuel storage (m^3)	0.1268	0.1516
Biomass storage (t)	0.2531	0.2531
Revenues (\$)	86.66	88.87
Costs(\$)	63.96	65.68
Purchased biomass (t)	1.373	1.373
Biofuel sold (m^3)	0.3975	0.2914
Bioenergy sold (MWh)	0.068	0.363
The biofuel used for bioenergy (m^3)	0	0.106

our model (with energy storage) is equivalent to the basic model (without energy storage). Table 5 shows the optimal solutions of two models ($\xi = \%5$). It shows the advantages of our model. When energy storage is considered, the profit increases by more than 2.2% comparing with the basic model (without energy storage). In addition, the amount of biofuel used for converting to bioenergy increases from 0 to $0.109 \times 10^7 m^3$. The biofuel storage is increased up to 19.6%. The amount of sold bioenergy is significantly increased. However, the amount of the purchased and stored biomass stay constant. As a result, the manager of biorefinery could obtain more profit from the same amount of purchased biomass.

In the next step, we show the difference between the two models under different perishability rates. Both models are run when the perishability rate changes from 0% to 100%. Figure 6 shows the results. First, our model (with energy storage) has always superiority over the basic model (without energy storage) under different perishability rates. Second, perishability also has a high negative impact on the basic model (without energy storage). It can reduce the profit by 10.5% when the perishability rate increase from zero. This shows the importance of considering perishability even in basic models (without energy storage). Third, above 50% in both models, biomass is not stored to avoid high perishability. Therefore, both models have a constant profit.

We now determine which parameters in our model (with energy storage) lead to its superiority compared with the basic model (without energy storage). To do so, some parameters which have more potential to affect the performance (of the biorefinery with energy storage) are investigated. These parameters are: 1) price of biofuel; 2) price of bioenergy; 3) biomass holding cost; 4) biofuel holding costs. Then, the values of these parameters are changed from their base case values (nominal value) to $\pm 20\%$ in order to see their impact on the profit.

Consider the parameter biomass holding cost as an example. We increase +20% the nominal value of the biomass holding cost used in the base case, and re-run the model. The obtained profit is compared with the optimal profit of the base case. Next, We decrease -20% the nominal value of the biomass holding cost used in the base case, and re-run

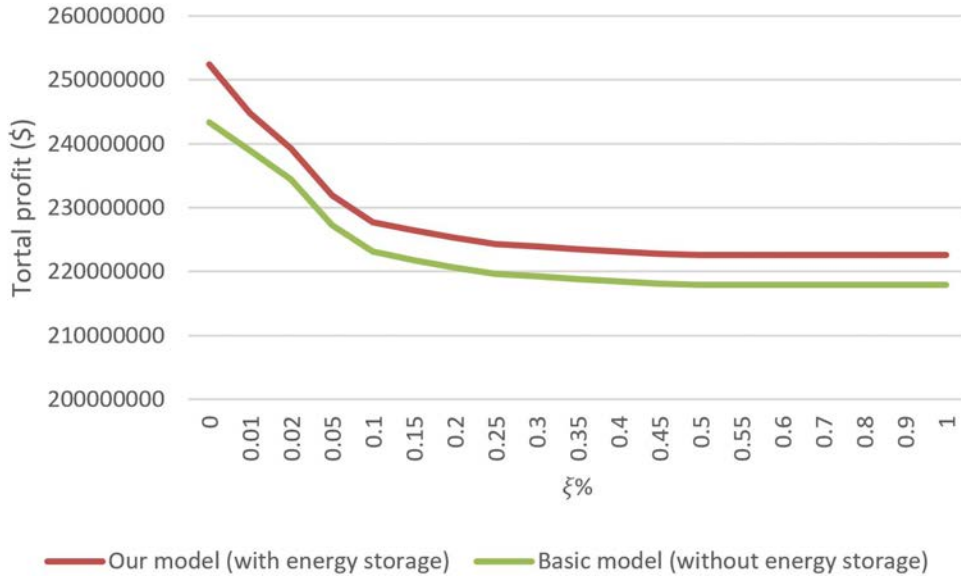


Figure 6: Profit of our model (with energy storage) and the basic model (without energy storage) models under different perishability rates

the model. The obtained profit is again compared with the optimal profit in the base case.

Table 6 presents the results. First, changing the holding costs by $\pm 20\%$ does not significantly change the total profit. Note that this is a production plant, not an intermediate storage site. The holding costs are not the main costs compared with other costs (e.g., production costs). In addition, we have different types of biomass, and not only one type that makes the model sensitive to holding costs.

Second, in both models, the impact of the biofuel holding cost fluctuation ($\pm 20\%$) on the profit is more than that of the biomass holding cost. This is more obvious in our model (with energy storage). According to Table 5, our model (with energy storage) stores more biofuel than the basic model (without energy storage), because our model (with energy storage) stores more biofuel to be used in two ways, directly to sell to the customer, or to convert it to bioenergy to be sold later. As a result, the biofuel holding cost fluctuation has more impact in our model (with energy storage). Once again, in the basic model (without energy storage), we have also biofuel storage, but we do not convert biofuel to bioenergy inside the biorefinery.

Third, the biofuel price has more effect on the profit of the basic model (without energy storage) than our model (with energy storage). However, the bioenergy price has more impact on our model (with energy storage) compared with the basic model (without energy storage). The amount of biofuel sold in the basic model (without energy storage) is more than our model (with energy storage). However, the amount of bioenergy sold in our model (with energy storage) is more than the basic model (without energy storage). This confirms the previous results (see Table 5).

Table 6

Percent changes in profit as function of parameter change (-20%, +20%)

Parameter	Percent change in parameter value of the models			
	-20%		+20%	
	Basic model	Our model	Basic model	Our model
Bioenergy price	-4.910%	-6.743%	4.910%	33.314%
Biofuel price	-71.440%	-44.257%	71.440%	67.821%
Biofuel holding cost	0.590%	0.691%	-0.590%	-0.599%
Bioamss holding cost	0.008%	0.008%	-0.008%	-0.007%

Fourth, in our model (with energy storage), the profit can be more impacted by the positive changes than negative changes. In other word, our model (with energy storage) is resilient to the negative changes. The reason of this superiority (compared with the basic model (without energy storage)) is the flexibility of our model (with energy storage) under negative changes. For example, when the price of bioenergy/biofuel decreases, since the model is looking for maximizing the profit, our model (with energy storage) switches to sell more biofuel/bioenergy which still has a high price, so that more profit (or less loss) is obtained. It means, our model (with energy storage) tries to neutralize the negative impact of the parameter (resiliency) by using other opportunities that are still available. Therefore, the model is resilient to fluctuation in the price of biofuel and bioenergy, as it adjusts the production quantity of each final product to maintain the profit. This is an interesting feature of our model (with energy storage).

6.5. Sensitivity analysis

In this part, a sensitivity analysis is performed to find the effect of the following parameters on the profit (compared with the base case that we used in Subsection 6.1)): (a) production costs; (b) maximum demand; (c) availability of biomass; (d) holding costs; (e) conversion rate; (f) price of products; (g) cost of purchasing biomass. The values of these parameters are changed over a reasonable range (-20% to +20%) to see the variation of the profit.

Figure 7 shows the results. First, the model is highly sensitive to the conversion rate. This shows the importance of perishability. Note that we, here, change the price of all products (all products at the same time). Second, our model is not sensitive to demand. The reason is that the proposed model in this study includes powerful tools such as biomass storage, biofuel storage, converting biofuel to bioenergy, energy storage, etc. All these tools help smoother production even with highly fluctuating demand.

The percentage of variation in the total profit with respect to base case solution.

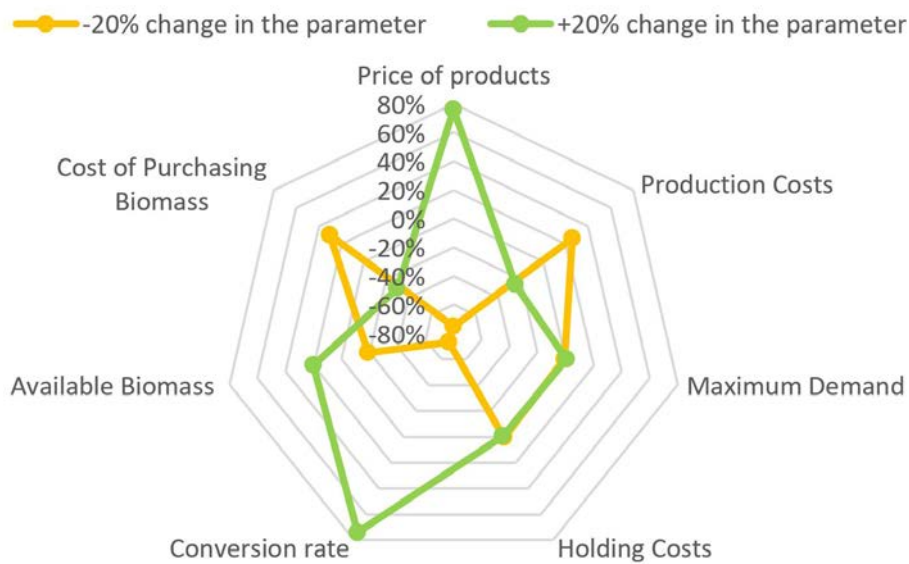


Figure 7: Sensitivity analysis with respect to the base case scenario

6.6. Some new assumptions

In this part, we want to add some new assumption to the proposed model for further analysis. We proposed our model (with energy storage) in Section 4. One interesting feature of this model is its simplicity, and it can be easily applied by biorefineries. In other words, our model(with energy storage) can be easily adjusted for new conditions. We want to show this feature (in this part) by considering some new assumptions (as new conditions). We found the following assumptions more interesting for this propose: 1) considering the fixed costs for the technologies and extra constraints for the capacities, 2) extending the planning horizon to three years including 36 monthly periods, 3) holding costs ($h_{b,t}^B, h_t^F$) are changed in each period (depending on the time), as well as 4) biomass purchasing costs ($c_{b,t}^B$) can change in each period. The mathematical formulation of the model with above mentioned assumptions is as follows, we name it as the model with new assumptions ("the model NA").

$$\begin{aligned}
\text{Maximize } & \sum_t (p^F \cdot F_t^C + p^E (E_t^B + E_t^F)) - \sum_b \sum_a \sum_t (c_{b,t}^B \cdot X_{b,a,t} + c_{b,t}^{BF} X_{b,a,t}^F + c_{b,t}^{BE} X_{b,a,t}^E) \\
& - \sum_t c_t^{FE} \cdot F_t^E - \sum_b \sum_a \sum_t h_{b,t}^B \cdot I_{b,a,t}^B - \sum_t h_t^F \cdot I_t^F \\
& - \sum_b \sum_t S_{b,t}^F \cdot Y_{b,t}^F - \sum_b \sum_t S_{b,t}^E \cdot Y_{b,t}^E - \sum_b \sum_t S_{b,t}^{FE} \cdot Y_{b,t}^{FE}
\end{aligned} \tag{14}$$

$$\text{Constraints (2) - (11)} \tag{15}$$

$$\sum_a X_{b,a,t}^F \leq Y_{b,t}^F \cdot \Psi_{b,t}^F \quad \forall b, t \tag{16}$$

$$\sum_a X_{b,a,t}^E \leq Y_{b,t}^E \cdot \Psi_{b,t}^E \quad \forall b, t \tag{17}$$

$$F_t^E \leq Y_t^{FE} \cdot \Psi_t^{FE} \quad \forall t \tag{18}$$

$$Y_{b,t}^F, Y_{b,t}^E, Y_t^{FE} \in \{0, 1\} \quad \forall b, t \tag{19}$$

In the objective function (14), we consider the setup costs for the technologies - converting biomass to biofuel ($S_{b,t}^F$), biomass to bioenergy ($S_{b,t}^E$), and biofuel to bioenergy ($S_{b,t}^{FE}$) - as well as the binary variables for activating the corresponding technologies ($Y_{b,t}^F, Y_{b,t}^E$ and $Y_{b,t}^{FE}$). In terms of constraints, we have four new capacity constraints, (16)-(19). Constraints (16) are for the technology converting biomass to biofuel. Constraints (17) are for the technology converting biomass to bioenergy. Constraints (18) are for the technology converting biofuel to bioenergy. Constraints (19) show the binary variables.

In terms of data for the model NA, we consider the same pattern of fluctuating demand as we used for the base

Table 7

Optimal solution value for the model NA

Profit (\$)	Revenue (\$)	Costs (\$)	The fresh stored biomass (t)	The old stored biomass (t)
$1.077166E + 8$	$3.619423E + 8$	$2.542257E + 8$	138774.27	99449.46

case (Section 5), and repeat it for second and third years (see Table 17). However, we change the maximum annual demand to $516442m^3$ for biofuel and 188805 MWh for bioenergy (Ghaderi et al. 2018, Rabbani et al. 2018). For biofuel holding costs (h_t^F), biomass holding costs ($h_{b,t}^B$), and biomass purchasing costs ($c_{b,t}^B$) in each period, different values are considered. We randomly generate them. In other words, for each time period, a random value is uniformly generated in the range $(-20\%, +20\%)$ around the corresponding nominal value considered in the base case that was independent of time (see Tables 13 and 15). Table 16 shows the processing facilities and their costs. For remainder parameters, we use the same values considered in the base case (see Section 5), and duplicate them for second and third years.

We run the model NA, Table 7 shows the initial optimal solution. The profits, revenues, and costs are shown in Table 7. In addition, the amount of stored biomass for fresh and old biomass are separately shown in Table 7. Table 7 shows only total biomass for whole planning horizon. However, Table 8 shows the biomass storage over three-year planning horizon in more details. In Table 8, the last column shows the amount of stored biomass in each year. The manager can use Table 8 to monitor the type and age of biomass as well as to know in which period and which year the biomass is stored, so perishability of biomass can also be managed over three years. The Table 8 also shows that the total amount of stored biomass is 238223.7 t.

Table 8
Amounts of inventory with different ages over three years

Biomass Type	Age	Storage	T												Total inventory	
			1	2	3	4	5	6	7	8	9	10	11	12	First year	
b = 4	a = 0	$I_{b=4,a=0,t}^B$	10359.127	11620	-	-	-	2422.976	-	1592.976	-	-	5616.173	-	31611.252	
	a = 1	$I_{b=4,a=1,t}^B$	-	6175.026	9393.472	-	-	-	-	-	-	-	-	2952.525	18521.023	
	a = 2	$I_{b=4,a=2,t}^B$	-	-	-	-	-	-	-	-	-	-	-	-	0	
	a = 3	$I_{b=4,a=3,t}^B$	-	-	-	-	-	-	-	-	-	-	-	-	0	
b = 5	a = 0	$I_{b=5,a=0,t}^B$	-	2899	2899	2899	-	-	-	-	-	-	2899	2899	14495	
	a = 1	$I_{b=5,a=1,t}^B$	-	-	-	878.586	-	-	-	-	-	-	-	-	878.586	
	a = 2	$I_{b=5,a=2,t}^B$	-	-	-	-	-	-	-	-	-	-	-	-	0	
	a = 3	$I_{b=5,a=3,t}^B$	-	-	-	-	-	-	-	-	-	-	-	-	0	
b = 4	a = 0	$I_{b=4,a=0,t}^B$	11620	11620	-	-	-	-	-	1592.976	-	-	5377.67	-	30210.646	
	a = 1	$I_{b=4,a=1,t}^B$	-	8693.105	11620	-	-	-	-	-	-	-	23	-	20313.105	
	a = 2	$I_{b=4,a=2,t}^B$	-	-	17.076	2960.098	-	-	-	-	-	-	-	-	2977.174	
	a = 3	$I_{b=4,a=3,t}^B$	-	-	-	-	-	-	-	-	-	-	-	-	0	
b = 5	a = 0	$I_{b=5,a=0,t}^B$	2899	2899	2899	2899	-	2588.117	-	-	-	2899	2899	2899	22881.117	
	a = 1	$I_{b=5,a=1,t}^B$	1417.497	2899	2899	2899	-	-	-	-	-	-	2899	2899	15912.497	
	a = 2	$I_{b=5,a=2,t}^B$	-	-	-	-	-	-	-	-	-	-	-	2899	2899	
	a = 3	$I_{b=5,a=3,t}^B$	-	-	-	-	-	-	-	-	-	-	-	-	0	
b = 4	a = 0	$I_{b=4,a=0,t}^B$	25	26	27	28	29	30	31	32	33	34	35	36	Third year	
	a = 1	$I_{b=4,a=1,t}^B$	11620	9651.696	-	-	-	2422.976	-	1592.976	-	-	-	-	25287.648	
	a = 2	$I_{b=4,a=2,t}^B$	-	11620	9651.696	-	-	-	-	-	-	-	-	-	21271.696	
	a = 3	$I_{b=4,a=3,t}^B$	-	-	2101.162	2960.098	-	-	-	-	-	-	-	-	5061.26	
b = 5	a = 0	$I_{b=5,a=0,t}^B$	2899	2899	2899	2899	-	-	-	-	-	-	-	-	0	
	a = 1	$I_{b=5,a=1,t}^B$	2899	1998.748	2899	2899	-	-	-	-	-	-	2692.614	-	14288.614	
	a = 2	$I_{b=5,a=2,t}^B$	919.378	-	-	-	-	-	-	-	-	-	-	-	10695.748	
	a = 3	$I_{b=5,a=3,t}^B$	-	-	-	-	-	-	-	-	-	-	-	-	919.378	

In terms of activated facilities, the optimally activated technologies in each periods over three years are shown in Table 9. As shown in Table 9, the technology converting sawmill waste to bioenergy is activated over 36 months of the planning horizon. The technology converting corn stover to biofuel is activated in 7 periods. The technology converting wheat straw to biofuel is activated in 13 periods. The technology converting switchgrass to biofuel is activated in 18 periods. The technology converting forest residues to bioenergy is activated in 24 periods. The technology converting biofuel to bioenergy is activated in 7 periods. One point in Table 9 is that the model NA prefers to activate the technology converting biofuel to bioenergy in fewer time periods comparing with other technologies. For example, in first year, sum of the periods when the first, second, and third technologies (biofuel generator) are activated are more than the periods when the technology converting biofuel to bioenergy is activated ($13 > 7$ periods). Likewise, sum of the periods when the fourth and fifth technologies (bioenergy generators) are activated are more than the periods when the technology converting biofuel to bioenergy is activated ($20 > 7$ periods). This shows the justification of the idea behind this study.

In other words, the main objective in proposed model is not converting a high level of biofuel to bioenergy, the priority is to sell biofuel and bioenergy generated from biomass. If it was necessary, the model activates the technology converting biofuel to bioenergy. This means that as long as the biorefinery is able to satisfy the demands with other technologies, it does not burn the valuable biofuel to generate bioenergy. Now, the question is that which parameter in the model leads to activation of the technology converting biofuel to bioenergy.

The answer of this question is that each parameter that disturbs the balance of the material flow in the production planning can lead to activating the technology converting biofuel to bioenergy. We show this by implementing two extra experiments. The first experiment is that we highly reduce the capacity of the technologies. We suppose that the available technologies have a very low level of capacity (e.g., instead of 5 MW, we consider 0.5 MW). We run the model for this case. We name this new model as "the model NA (low capacity)". Table 10 shows the results. Table 10 shows that the generated shock to the material flow (the capacity limitation) leads to a disturbance to the balance in the material flow. Therefore, in this case, the technology converting biofuel to bioenergy would be activated in more periods (compare Tables 10 with Table 9) to bring back the balance. Note that balance leads to more production, more customer satisfaction (demand), and more profit for the biorefinery.

The second experiment is that we bring back the initial capacity (not using the very low capacity), but we change several other parameters at the same time. These parameters are availability of biomass, perishability, and demand. We suppose that there is no fluctuation in the availability of biomass, as well as the demand. They are constant, and equal to $1/12$ for each period (month) of each year. In addition, we suppose that there is no biomass perishability ($\xi = 0\%$). We run the model for this case. Table 11 shows the results. Table 11 shows that the technology converting biofuel to bioenergy is not activated over planning horizon. In other words, we have an acceptable balance in the material flow. Therefore, the model does not activate the technology converting biofuel to bioenergy to bring back the balance.

Table 9
Active technologies in three years

Technology converting	Capacity	T																								Total	
		1	2	3	4	5	6	7	8	9	10	11	12	12	12	12	12	12	12	12	12	12	12	12	12	First year	Second year
Technology converting	Capacity	13	14	15	16	17	18	19	20	21	22	23	24	24	24	24	24	24	24	24	24	24	24	24	24	3	3
Corn stover to biofuel	200000 t/month	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	3	3
Wheat straw to biofuel	200000 t/month	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	5	5
Switchgrass to biofuel	200000 t/month	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	5	5
Forest residues to bioenergy	5 MW	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	8	8
Sawmill waste to bioenergy	5 MW	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	12	12
Biofuel to bioenergy	5 MW	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	3	3
Technology converting	Capacity	13	14	15	16	17	18	19	20	21	22	23	24	24	24	24	24	24	24	24	24	24	24	24	24	3	3
Corn stover to biofuel	200000 t/month	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2
Wheat straw to biofuel	200000 t/month	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	3	3
Switchgrass to biofuel	200000 t/month	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	7	7
Forest residues to bioenergy	5 MW	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	8	8
Sawmill waste to bioenergy	5 MW	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	12	12
Biofuel to bioenergy	5 MW	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2
Technology converting	Capacity	25	26	27	28	29	30	31	32	33	34	35	36	36	36	36	36	36	36	36	36	36	36	36	36	2	2
Corn stover to biofuel	200000 t/month	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2
Wheat straw to biofuel	200000 t/month	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	5	5
Switchgrass to biofuel	200000 t/month	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	6	6
Forest residues to bioenergy	5 MW	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	8	8
Sawmill waste to bioenergy	5 MW	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	12	12
Biofuel to bioenergy	5 MW	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2

Table 10
Active technologies in three years with lower capacities

		T																																				Total					
Technology converting	Capacity	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	First year	Second year				
Corn stover to biofuel	70000 t/month							1	1	1	1	1	1																										6				
Wheat straw to biofuel	70000 t/month	1	1	1	1		1	1	1																															7			
Switchgrass to biofuel	70000 t/month	1	1				1	1	1	1	1	1	1																											9			
Forest residues to bioenergy	0.5 MW	1	1				1	1	1	1	1	1	1																											9			
Sawmill waste to bioenergy	0.5 MW	1	1	1	1	1	1	1	1	1	1	1	1																											12			
Biofuel to bioenergy	0.5 MW			1	1		1	1	1	1	1	1	1																											8			
Technology converting	Capacity	13	14	15	16	17	18	19	20	21	22	23	24																														
Corn stover to biofuel	70000 t/month							1	1	1	1	1																													5		
Wheat straw to biofuel	70000 t/month	1	1	1	1		1	1	1																																7		
Switchgrass to biofuel	70000 t/month	1	1				1	1	1	1	1	1	1																												9		
Forest residues to bioenergy	0.5 MW	1	1				1	1	1	1	1	1	1																												9		
Sawmill waste to bioenergy	0.5 MW	1	1	1	1	1	1	1	1	1	1	1	1																												12		
Biofuel to bioenergy	0.5 MW			1	1		1	1	1	1	1	1	1																												9		
Technology converting	Capacity	25	26	27	28	29	30	31	32	33	34	35	36																														
Corn stover to biofuel	70000 t/month							1	1	1	1	1	1																													6	
Wheat straw to biofuel	70000 t/month	1	1	1	1		1	1	1	1	1	1	1																													8	
Switchgrass to biofuel	70000 t/month	1	1				1	1	1	1	1	1	1																													9	
Forest residues to bioenergy	0.5 MW	1	1				1	1	1	1	1	1	1																													9	
Sawmill waste to bioenergy	0.5 MW	1	1	1	1	1	1	1	1	1	1	1	1																													12	
Biofuel to bioenergy	0.5 MW			1	1		1	1	1	1	1	1	1																													8	

Table 11
Active technologies under a constant demand and biomass availability as well as no perishability

Technology converting	Capacity	T												Total	
		1	2	3	4	5	6	7	8	9	10	11	12	First year	Second year
Corn stover to biofuel	200000 t/month	1	1	1	1	1	1	1	1					5	
Wheat straw to biofuel	200000 t/month	1	1	1	1				1	1	1	1		6	
Switchgrass to biofuel	200000 t/month	1		1		1		1	1		1			6	
Forest residues to bioenergy	5 MW	1	1	1	1	1	1	1	1	1	1	1		9	
Sawmill waste to bioenergy	5 MW	1	1	1	1	1	1	1	1	1	1	1	1	12	
Biofuel to bioenergy	5 MW													0	
Technology converting	Capacity	13	14	15	16	17	18	19	20	21	22	23	24	Second year	
Corn stover to biofuel	200000 t/month	1				1						1	1	4	
Wheat straw to biofuel	200000 t/month		1		1	1	1		1			1		5	
Switchgrass to biofuel	200000 t/month			1				1		1				4	
Forest residues to bioenergy	5 MW	1	1	1			1		1	1		1		6	
Sawmill waste to bioenergy	5 MW	1	1	1	1	1	1	1	1	1	1	1	1	12	
Biofuel to bioenergy	5 MW													0	
Technology converting	Capacity	25	26	27	28	29	30	31	32	33	34	35	36	Third year	
Corn stover to biofuel	200000 t/month		1	1		1								4	
Wheat straw to biofuel	200000 t/month	1		1										2	
Switchgrass to biofuel	200000 t/month			1				1	1		1			4	
Forest residues to bioenergy	5 MW	1					1	1	1					4	
Sawmill waste to bioenergy	5 MW	1	1	1	1	1	1	1	1	1	1	1	1	12	
Biofuel to bioenergy	5 MW													0	

Table 12Optimal solution of the model Na ($\times 10^6$), as well as the model NA (low capacity) ($\times 10^5$)

	NA without ES	NA with ES	NA (low capacity) without ES	NA(low capacity) with ES
Profit (\$)	106.54	107.71	222.36	226.54
Biofuel storage (m^3)	1.006	1.056	0.38446	0.35910
Biomass storage (t)	0.929	0.138	0.37552	0.47194
Revenues (\$)	359.86	361.94	737.54	751.44
Costs(\$)	253.31	254.22	515.17	524.89
Purchased biomass (t)	5.680	5.680	11.88	11.88
Biofuel sold (m^3)	1.549	1.549	2.872	2.188
Bioenergy sold (MWh)	0.540	0.566	1.871	3.764
The biofuel used for bioenergy (m^3)	0	0.0248	0	0.68350

Finally, we want to show that this balance generated by energy storage has advantages for the biorefinery. To do so, we choose two models, 1) the model NA, 2) the model NA (low capacity). We run these two models once with energy storage, and once without energy storage ($\eta^{FE} = 0$). Table 12 shows the results. In Table 12 ES means Energy Storage. Table 12 confirms that in the both models (i.e., the model NA, as well as the model NA (low capacity)), energy storage generating the balance leads to more profit over three-year planning horizon.

7. Conclusion

We developed and solved a multi-period production planning model for a biorefinery that transforms different types of biomasses into either bioenergy or biofuel. The biomass can be stored but its quality is deteriorated over time, which incurs a lower yield. The biofuel can also be stored to be transformed later to bioenergy. The applicability of the developed model was illustrated by the numerical example. Extensive numerical experiments were performed to understand the behavior of the model and derive managerial insights. The results showed that the higher the biomass perishability rate the lower the profitability of the biorefinery, but there is a threshold value on the biomass perishability rate above which perishability does not have any more impact on the profit. The biofuel storage is an important feature of our model. While bioenergy cannot be stored and biomass storage leads to reducing its quality, the biofuel can be stored and transformed later into bioenergy to match supply with demand. We showed that this results in considerable profit increase and smoother production at the facility even under a high fluctuation in bioenergy selling price and demand.

Our modeling framework comes with limitations that offer avenues for future work directions. First, it is interesting to consider the uncertainty on the supply of biomass and evaluate its impact on production strategy and profit. Second, in order to study the potential of exploiting high peak-load prices for energy in a variable pricing environment (e.g. electricity), bioenergy price and demand uncertainties can be incorporated into the model. Third, the problem in this study can be also solved by applying other methods. For example, risk pooling, putting together the demands and supplies, matching them using the stored biofuel. Then, the social systematic approach can be applied. Comparing the results of different methods would be interesting. Finally, applying our model to a real case study would certainly require to make some adjustments in the modeling framework and constraints.

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Table 13
Characteristics of biomass

Biomass	Annual available (t)	Moisture content (%)	Energy content (GJ/t)	Energy content ^d biofuel (GJ/m ³)	Purchase cost (\$/ton)
Corn stover ^a	195457	24.1	18.80	≈ 42.5 ^d	20
Wheat straw ^a	1167797	23.53	18.65	≈ 42.5 ^d	21
Switchgrass ^b	11522646	26.5	17.80	≈ 42.5 ^d	26
Forest residues ^c	821700	29	14.65	-	24
Sawmill waste ^c	26091	30.5	13.71	-	19

^aBairamzadeh et al. (2015)

^bGhaderi et al. (2018)

^cCamero et al. (2015)

^dIrREA 2020

Appendices:

Appendix A. Biomass data

A summary of different types of biomass used in this study, and the features such as moisture content, energy content, annual availability, and purchase costs, are presented in Table 13.

Biomass has a perishable nature (Tavanandi et al. (2018); Castillo-Villar et al. (2017); Valdovinos-García et al. (2020)). Biomass could not be stored in the warehouse for a long time. The chemical reactions continuously occur and lead to losses of the valuable materials in the biomass over storage time (Fuller (1985); Larson et al. (2015); Kenney et al. (2013)). The perishability of biomass has an important role in the performance of the production process (Rentizelas et al. (2009)).

Biomass perishability is defined (in this study) as the reduction in the values of: i) energy content (higher heating value HHV) ($\frac{\text{GJ}}{\text{t}}$) (Channiwala and Parikh (2002)), and ii) oil yield ($\frac{\text{m}^3}{\text{t}}$) (Fuller (1985)). This reduction in the value is based on biomass aging.

Appendix B. Conversion technology data The data related to the conversion technologies used in this study are presented in Table 14 and 16.

Appendix C. Price, holding cost, and demand data

The holding costs, as well as selling price of each m^3 of biofuel and each MWh of bioenergy are shown in Table 15. Table 17 shows the demand of biofuel and bioenergy in each period (month).

Table 14

The assigned technology, and the processing cost for each kind of fresh biomass.

Technology	Yield (unit of product output/ unit of the feedstock input)					
	Corn stover (m^3/t) ^a	Wheat straw (m^3/t) ^a	Switchgrass (m^3/t) ^b	Forest residues (MWh/t) ^{c,d}	Sawmill wastes (MWh/t) ^{c,d}	Biofuel ^{e,f} (MWh/ m^3)
1. Biochemical (Fermentation): Biochemical conversion process	0.272	0.270	0.313	-	-	-
2. Thermochemical (Combustion): Thermochemical conversion process Efficiency 23.5%	-	-	-	0.956	0.895	2.776

^aBairamzadeh et al. (2015)

^bGhaderi et al. (2018)

^cCamero et al. (2015)

^dAkhtari et al. (2018)

^eWickwire (2007)

^fMahjoub et al. (2020)

Table 15

Selling prices, holding costs.

Products	Selling price (\$) ^a	Holding cost (\$) ^{b,c}
Biofuel (bioethanol m^3)	204	5.283
Bioenergy (electricity MWh)	81	-
Biomass (t)	-	0.0375

^a NIOPDC 2014

^b Bairamzadeh et al. 2018

^c Ghaderi et al. 2018

Table 16

Processing facilities and their costs

Processing facility type	Capacity	Variable cost (\$/ton)	Fixed cost (\$/moth)
Biochemical (Fermentation) ^{a,b}	70000 t/month	37.1	221122
Biochemical (Fermentation) ^{a,b}	140000 t/month	31.3	411695
Biochemical (Fermentation) ^{a,b}	200000 t/month	21.0	588227
Thermochemical (Combustion) ^{c,d}	0.5 MW	101.4	28012
Thermochemical (Combustion) ^{c,d}	2 MW	43.9	102394
Thermochemical (Combustion) ^{c,d}	3 MW	33.4	144868
Thermochemical (Combustion) ^{c,d}	5 MW	16.5	222078

^aBairamzadeh et al. (2015)

^bGhaderi et al. (2018)

^cCamero et al. (2015)

^dWickwire (2007)

Table 17

Demand of products

Demand	T											
	1	2	3	4	5	6	7	8	9	10	11	12
Biofuel ^a	3.9%	4.9%	8.7%	9.7%	9.7%	9.7%	9.7%	9.7%	9.7%	4.9%	9.7%	9.7%
Bioenergy ^b	4.6%	3.6%	3.6%	9.2%	9.2%	9.2%	9.2%	9.2%	12.0%	11.1%	10.2%	9.2%

^aNIOPDC (2014)

^bEnergy (2017)