Producing drop-in biofuel from feedstock grown on marginal land in Sumba island, Indonesia: a systems dynamics analysis

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Abstract. To improve sustainability, liquid biofuel can be produced by growing biomass feedstock on marginal land and using innovative and appropriate conversion technology under development. Throughout the Indonesia Archipelago, oil fuel imports are high, and marginal land is abundant. This study assessed future potential for drop-in biofuel (DBF) production from Pongamia pinnata oilseed crops as driven by various policy and technical parameters. A systems dynamics approach was applied and a model developed to simulate the dynamics of developing DBF technology at the national level. The potential use of marginal land in Sumba Island was taken as a case study to assess the projected DBF production as well as any increase in the gross regional domestic product (GRDP) by 2045. The model outputs showed there is an interrelationship between biofuel development and political elements, especially the level of sense of urgency (SU) by the country’s President. In enhancing DBF production, and hence increasing GRDP, SU can be increased and sustained by empowering a future vision for the nation. Given a maximum future vision over time, 100% of liquid fuel self-sufficiency could be reached in Sumba by 2033. Then the GRDP increase from DBF-related revenues would exceed the current total GRDP.

1. Introduction
Indonesia is a large archipelago that is highly dependent on oil imports. On the other hand, abundant marginal land is available for growing energy crops. In addition, a conversion technology for drop-in biofuel (DBF) production has been under development. Improving liquid fuel self-sufficiency through sustainable biofuel production and utilization could be feasible both nationally as well as locally, especially on small islands. In Indonesia where fuel distribution is a challenge, developing DBF using feedstock grown on marginal land would benefit energy security.

In analyzing marginal land issues, Sumba, the iconic island for developing renewable energy systems was chosen as a case study given that petroleum oil resources are absent. Analysis of DBF technology readiness was conducted at the national level. Political elements drive the progress rate for marginal land development as well as DBF technology innovation.

Delayed actions in degraded land restoration, as well as energy technology innovation, can lead to acceleration of negative impacts on the economy, society, and environment in longer-term [1,2]
This study aims to better understand how policy implementation and liquid biofuel implementation could affect to one another. Considering time factor, it assessed political dimensions which are lacking in existing assessments of bioenergy deployment and sustainability.

For assessing impacts on liquid fuel self-sufficiency and gross regional domestic product (GRDP) systems that contain inter-relationships, a systems dynamics approach was applied \[3,4\].

In this paper, Section 2 describes the strategy of DBF production from marginal land-based feedstock; Section 3 provides a literature review on assessment of the strategy; Section 4 explains the methodology which includes the model development; Section 5 presents results and discussion and the conclusions are given in Section 6.

2. DBF Production from Feedstock Grown on Marginal Land

2.1. Drivers for liquid biofuel implementation
Liquid fuel demand will remain significant in the long term, especially for heavy-duty vehicles, marine ships, planes, and light-duty vehicles. In 2017, liquid fuel consumption in Indonesia reached around 70 GI of which around 30 GI was imported \[5\]. The high rate of oil imports has threatened the national economy in relation to the balance of trade (BOT).

On the other hand, the use of liquid biofuel in Indonesia has fluctuated and been unsatisfactory. It has progressed significantly only when BOT is in trouble, which drives the sense of urgency for accelerating biofuel utilization by the President who has the utmost cross-sectoral authority.

To reduce oil imports, Indonesia could produce and use DBF from biomass feedstock grown on marginal land as an integrated strategy. As the progress is influenced by the government’s urgency to increase liquid fuel self-sufficiency, it is necessary to increase and maintain the urgency at high level. For example, by applying a driver that acts anticipatively rather than responsively \[6\] as does the pressure from BOT.

The anticipative driver could be a future vision that can be adopted from The Constitution 1945 preamble, paragraph four, which states the nation’s idea to be a sovereign country. Moreover, the 7th President wrote, “The Indonesian Dreams 2085” \[7\] which included for Indonesia to become an independent country. This has been put into a shorter-term vision, “Golden Indonesia 2045” marking the 100th Independence Day as an important development milestone \[7\].

2.2. DBF technology development
Conventional liquid biofuels such as bioethanol and biodiesel have limitations in high-level blends with petroleum fuels. DBFs allow more flexible utilization in the whole existing infrastructure thanks to their equivalent characteristics with petroleum fuels.

This study assessed the indigenous DBF conversion technology being developed at the Institute of Technology of Bandung, a tertiary educational institution in Indonesia. “Hydrodeoxygenation” route requires hydrogen in the production process and has progressed closer to commercial scale, whereas “decarboxylation of metal soap” route can be undertaken without hydrogen and has better economic feasibility at a lower production scale \[8\].

Financial support from the government is very important for the success of degraded land utilization \[9\] as well as in new technology development for energy production \[10\]. SU level determines how effective the support would be provided.

The role of urgency in accelerating a technology innovation was shown in the development of the “Houdry Process”, a primary technology applied in oil refineries up to the present. It took only three years from the initial concept to commercial production in 1942 \[11\], urged by the Allied Forces commander in overcoming fuel shortages.

2.3. Marginal land potential
Sumba is an iconic island for renewable energy in Indonesia that has around 900,000 population on an area of 1.1 Mha including around 475,000 ha of marginal land distributed across East Sumba and Central
Sumba regencies [12,13,14,15,16]. It has no oil resources but the marginal land is around 2% of around 25 Mha categorized as “critical” and “very critical” in Indonesia [16]. Much of this land has the potential for growing crops [17,18].

*Pongamia pinnata* was chosen as a preferred crop on marginal land-based on several criteria including high energy wood, nitrogen-fixing, fast-growing and able to grow on high-salinity soil. Sumba climate conditions and a soil test result indicated that *Pongamia* can be cultivated in Sumba. Therefore, having good availability of data and information, it was used as the model input. However, determination of the most suitable on-site crop should be based on further assessments including field trials.

2.4. Approach for the assessment

DBF production using marginal land comprise several key components: national supporting policy; conversion technology readiness; marginal land preparedness; DBF commercial production, and liquid fuel import demand. The components have interdependent relationships so that a systems dynamics approach was used for the assessment using Sumba as the case study.

A delay in any of these components leads to a delay in all components and sectors, thus, time is a crucial factor. Therefore, the political aspect of biofuel sustainability that is currently lacking was included in the assessment.

Systems dynamics modeling commonly assesses multi-disciplinary systems that involve various sectors and thus are capable of assisting stakeholders in communicating and playing a role in implementing and evaluating the strategy based on scenarios. In developing countries, a systems dynamics model could be a user-friendly tool for policymakers and non-experts, thanks to their transparency in generating results, flexibility in using input data and information, and ease of revision.

3. Assessment of The Strategy

Out of existing studies on liquid biofuel assessments, no study was found that assessed marginal land use and conversion technology innovation in an integrated fashion.

In Indonesia, before 2018, two studies that integrated conventional feedstock and technology were carried out by Rahmadi, Aye [19] and Jupesta [20], but neither applied a systems dynamics approach.

Assessments that used system dynamics approach have been conducted in Columbia [21], Iran [22], Latvia [23], Malaysia [24], USA [25], and South Africa [26]. However, none of them covered the inter-relationship between political sustainability and liquid biofuel sustainability.

Among bioenergy sustainability dimensions [27, 28 in [29]] as studied by Bautista, Enjolras [30], politics and technology are the least assessed in the literature. Unlike existing studies, this study explicitly shows political and technological sustainability which interrelate to one another allowed by treating policy parameter as an endogenous variable.

4. Methodology

Systems dynamics methodology was used by developing a model that has the capability of handling feedback loops. The main steps in the methodology comprise conceptualization, problem definition, model structuring, model validation, and scenario analysis.

The problem was defined using a causal loop diagram that shows inter-relationships between the liquid fuel import demand that indicates liquid fuel self-sufficiency, the proposed strategy, and the policy (Figure 1). The liquid biofuel development and the policy affect one another. An increase in policy increases biofuel production which affects the consumption, which in turn affects the policy itself.
Figure 1. Problem definition in a causal loop diagram showing a feedback loop between policy and liquid biofuel development.

4.1. The model structure
The systems dynamics model was developed by building a stock and flow diagram to perform quantitative simulations. Determination of variables and their relationships refer to general theory or knowledge including from literature analysis, work experience, interviews, and personal communications.

The model was developed using Stella® Architect software applying the time horizon 2018-2045. The model consists of seven sectors representing policy, technology readiness, marginal land preparedness and liquid fuel import demand from a national perspective and feedstock production DBF production and GRDP on Sumba. Quantifying national-level indicators relating to the cultivation area was calculated using the multiplier factor from the Sumba area.

Methods used for data collection consisted of literature analysis, semi-structured interviews, focus groups, and personal communications as follows.

- Sumba marginal land development.
  This stage identified support and barriers that might exist in the program implementation. It involved landowners and policymakers in East Sumba and Central Sumba.

- Soil test.
  This work was conducted to analyze the suitability of the soil for growing the Pongamia energy crop on Sumba marginal land. Soil samples were taken from six locations across the two regencies and tests were conducted at an accredited soil laboratory in Indonesia.

- Focus group of DBF conversion technology
  This activity aimed to identify factors that could influence success in technology development. Funding continuity up to the commercialization was the greatest challenge.

- Focus group of cross-sectoral policy
  This focus group aimed to capture any cross-sectoral policies at the national level that might have not been considered in the study.

Important variables in the model are shown in a simplified stock and flow diagram (Figure 2).
4.1.1. Policy sector. The policy sector was modelled using variables that influence policy parameters, especially the sense of urgency (SU) by the President, which drives the liquid fuel self-sufficiency through DBF production.

SU can be maintained high and stable by the realization of a future vision for the nation. SU (dimensionless unit) ranges from zero to one where the initial value of SU is set 1 and the increasing in SU (\( r_{IU} \)) is calculated as:

\[
 r_{IU} = \left( PBOT \times (1 - WVS) + FVS \times WVS \right)/t_{SU}
\]

(1)

where PBOT (dimensionless unit) is pressure from a balance of trade (section 2.1), WVS (dimensionless unit) is weight to vision, FVS (dimensionless unit) is future vision power, and \( t_{SU} \) (years) is time to change urgency.

The national balance of trade (BOT) is influenced by liquid fuel imports as determined by liquid fuel consumption volume and price. To make the model simpler, this study assumed that liquid biofuel consumption is equal to liquid biofuel production from both Pongamia DBF and palm biodiesel. When
DBF technology is commercially ready but marginal land feedstock is still unavailable, DBF will be initially produced from existing palm oil feedstock.

Thus, national liquid fuel import demand (NLI, in l/yr) is calculated as:

$$NLI = NLD - (NOP + NBP)$$

where NLD is national liquid fuel demand (kL/yr); NOP is national oil fuel production (kL/yr), and NBP is national liquid biofuel production (kL/yr).

### 4.1.2 Technology readiness sector.

The technology readiness (TR) sub-model is changed by the provision of support for the investment by the sectors in-charge. In this study, support increases TR through accumulated investment driven by the SU as an input from the policy sub-model. This sub-model simulates the estimation of the future time when the technology will become ready.

### 4.1.3 Sumba marginal land preparedness sector.

This sub-model shows the dynamics of conversion from marginal land available for energy crops into Sumba’s developed marginal land area, through marginal land development rate.

Based on the interviews with landowners and local government officials, factors that influence marginal land development rate in Sumba comprise infrastructure readiness, local government commitment, landowners willing to cultivate, land status clarity, and pressure from TR to land development. As in the technology readiness progress rate, all those factors are driven by SU.

This sub-model determines delay in planting the crop which affects delay in DBF production. Planting delay reflects the difference between the actual and desirable year of planting start.

$$PLD = AYP - DYP$$

where PLD is planting delay (years), AYP is actual year of planting start (when the feedstock becomes available for running the first DBF production plant), and DYP is desirable year of planting start (the marginal land developed area can provide sufficient feedstock to start a DBF production plant) when future vision is maximum.

### 4.1.4 Sumba feedstock production sector.

This sub-model calculates biomass feedstock grown on marginal land for DBF production at the island level based on the crop growth characteristics. Parameter values that relate to *Pongamia* crop’s growth properties can be estimated [31]. Crop growth was simulated by applying a cohort structure to show the pattern of oilseed production by estimating expected yields based on the expected growth factors of each cohort. The establishment of a blocking system linked to the crop rotation cycle is useful in reducing investment risk.

The sub-model is divided into 15 age cohorts, each with a tree stock, an oilseed yield flow, a growing rate flow, and a planting and growing flow that represents the associated year as well as the planted block area.

### 4.1.5 Sumba DBF production sector.

This sub-model calculates DBF production from Sumba marginal land feedstock, which is also used for the estimation at the national level.

Sumba DBF production \(r_{DP}\) in kL/yr is constrained by production capacity and feedstock availability, and calculated as:

$$r_{DP} = \text{MIN}(DP, OFD \times OFL)$$
where DP (kL/yr) is DBF production capacity stock, OFD (kL/yr) is oil feedstock for DBF production, and OFL (dimensionless unit) is oil feedstock conversion rate.

4.1.6. Sumba liquid fuel supply and demand sector. This sub-model calculates liquid fuel self-sufficiency through DBF production and use, which is a very important indicator since Sumba Island has no crude oil resources to meet the liquid fuel demand.

Sumba liquid fuel self-sufficiency (SLF, in dimensionless unit) is calculated as:

\[
SLF = \frac{SLD - SLI}{SLD} \backslash (5)
\]

\[
SLI = SLD - r_{DP} \quad (6)
\]

where SLD is Sumba liquid fuel demand (kL/yr) and SLI is Sumba liquid fuel import demand (kL/yr).

4.1.7. Economic sector. This sub-model calculates the potential economic benefits from DBF implementation in Sumba using the indicators of the increase in the gross regional domestic product (GRDP) and the national foreign exchange savings (FES).

Sumba’s GRDP increase arises from DBF, oilseeds, and woodfuel (SGI, in USD/yr) calculated as:

\[
SGI = r_{DC} \times DBP \times l/k + SOH \times OSP + \frac{SWH}{WCT} \times WFP \quad (7)
\]

where \( r_{DC} \) (kl/yr) is DBF production, DBP (USD/l) is DBF price, SOH (t/yr) is oilseeds for harvest, OSP (t/yr) is oilseeds price, SWH (USD/t) is woodfuel for harvest, WCT (years) is woodfuel consumption time, and WFP (USD/t) is woodfuel price. As a comparison, combined total GRDP for East Sumba and Central Sumba in 2013 was around USD 200 million (BPSKSTM [13]; [12]).

The national foreign exchange saving (FES, in USD/yr) from DBF implementation using feedstock grown on marginal land is calculated as:

\[
FES = NDN \times DBP \quad (8)
\]

where NDN is national DBF consumption (kL/yr) which is assumed equal to national DBF production, and DBP is DBF price (USD/kL).

DBF price is calculated as Pongamia oil feedstock cost plus DBF conversion cost and DBF profit margin, subtracted by by-products revenues. The key variable in this sub-model is the cost of Pongamia oil feedstock which is interdependent with the rate of changes in Pongamia oil cost.

The values of parameters in the involved sectors are shown in Table 1.

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**Table 1.** Parameters’ values applied in the model.

| Sector              | Parameter                        | Type          | Value | Unit       | Notes/Source       |
|---------------------|----------------------------------|---------------|-------|------------|--------------------|
| Policy              | Initial value (IV) for SU        | Constant      | 1     | dimensionless | Estimation         |
|                     | Gas export volume                | Time series   |       | billion cubic feet/yr | [32]; Appendix     |
|                     | Crude oil export volume          | Time series   |       | bbl/yr     | [32]; Appendix     |
|                     | Non-oil & gas export value       | Time series   |       | USD/yr     | assumed 5% growth of historical data [33]; Appendix |
| Sector | Parameter | Type | Value | Unit | Notes/Source |
|--------|-----------|------|-------|------|--------------|
| Non-oil & gas import value | Time series | USD/yr | | | assumed 5% growth of historical data [33]; Appendix |
| LPG import demand volume | Time series | Mt/yr | | | [32]; Appendix |
| Crude oil import volume | Time series | bbl/yr | | | [32]; Appendix |
| Gas import volume | Time series | billion cubic feet/yr | | | [32]; Appendix |
| Oil price | Time series | USD/barrel | | | [34]; Appendix |
| Gas price | Time series | USD/MMBtu | | | [35]; Appendix |
| Palm oil price | Time series | USD/t | | | Extrapolating historical data of [36]; Appendix |
| DBF technology readiness | IV technical readiness (TR) | Constant | 0.5 | dimensionless | Estimation |
| | Desired TR | Constant | 1 | dimensionless | Max limit |
| | Expected time to progress TR | Constant | 5 | years | [37]; [38] |
| | Expected time of post-technical readiness | Constant | 3 | years | [39] |
| Marginal land preparedness | IV marginal land available for bioenergy | Constant | 200,000 | ha | Required minimum area for meeting Sumba liquid fuel demand in 2045 (342k kl/yr) |
| | Expected time to develop land | Constant | 3 | years | Estimation |
| | IV infrastructure readiness | Constant | 0.2 | dimensionless | Site visit and interview |
| | IV local government commitment | Constant | 0.6 | dimensionless | Site visit and interview |
| | IV land certification | Constant | 0.2 | dimensionless | Site visit and interview |
| | IV landowners respect | Constant | 0.9 | dimensionless | Site visit and interview |
| | IV landowners understanding | Constant | 0.5 | dimensionless | Site visit and interview |
| Oil feedstock production | Trees per ha | Constant | 350 | tree/ha | [31] |
| | Crop rotation cycle | Constant | 15 | years | Considering the peak period of Pongamia oilseeds |
| Sector                          | Parameter                                      | Type            | Value                        | Unit       | Notes/Source |
|--------------------------------|-----------------------------------------------|-----------------|------------------------------|------------|--------------|
| Cultivation time before first harvest | 8th year.                                     | Constant        | 3                            | years      | [31]         |
| Growth year 1-15               |                                               | Constant        | 0.5e-3; 2.5e-3; 17e-3; 25e-3; 30e-3; 20e-3; 35e-3; 25e-3; 0; 0; 0; 0; 0; 0. | t/tree     | [31]         |
| Oilseeds yield 1-15            |                                               | Constant        | 0.00; 0.00; 0.00; 0.01; 0.01; 0.013; 0.014; 0.025; 0.025; 0.025; 0.025; 0.025; 0.025. | t/tree     | [31]         |
| Oil content in seeds           |                                               | Constant        | 0.4                          | dimensionless | [31]         |
| Woodfuel yield per tree        |                                               | Constant        | 0.01                         | t/tree     | Estimation   |
| DBF production                 | DBF plant construction time                  | Constant        | 2                            | years      | Common practice of similar oleochemical plants |
|                               | DBF capacity life time                        | Constant        | 20                           | years      | Common practice |
|                               | Oil feedstock conversion                      | Constant        | 0.76                         | dimensionless | [40]         |
|                               | Desired DBF production per plant              | Constant        | 50,000                       | kl/yr      | [8]          |
| Liquid fuel import demand      | Sumba liquid fuel demand                      | Time series     | kl/yr                        |            | 2018-2025: [41]; 2025-2045: assumed 5% growth; Appendix |
|                               | National liquid fuel demand                   | Time series     | kl/yr                        |            | [32]; Appendix |
### Sector Parameter

| Sector                                | Parameter                                      | Type          | Value       | Unit     | Notes/Source |
|---------------------------------------|-----------------------------------------------|---------------|-------------|----------|--------------|
| National oil fuels production        | Time series                                   |               |             |          |              |
| National DBF export quota            | Constant                                       | 1 million     | kl/yr       |          | Assumption   |
| National to Sumba marginal land area multiplier | Constant                                       | 50            | dimensionless |          | Estimation   |
| Oil palm plantation area             | Constant                                       | 14            | Mha         |          | [42]         |
| Palm oil productivity target         | Constant                                       | 5             | t/ha        |          | [42]         |
| Fraction palm oil consumption for food & oleo excluding biofuel | Constant                                       | 0.1           | dimensionless |          | Current trend |
| Fraction palm oil for export         | Constant                                       | 0.1           | dimensionless |          | Assumption   |
| National biodiesel export quota      | Constant                                       | 1 million     | kl/yr       |          | Assumption   |
| GRDP                                 | Constant                                       | 0.001         | dimensionless |          | Assumption (well controlled by government) |
| Pongamia oil feedstock cost growth rate | Constant                                       | 15            | USD/t       |          | [31]         |
| Oilsseeds price                      | Constant                                       | 50            | USD/t       |          | Assumption   |
| Woodfuel price                       | Constant                                       | 0.1           | dimensionless |          | Common practice in oleochemical industries |
| DBF profit margin                    | Constant                                       | 0.36          | USD/l       |          | Assumption based on existing study [43] [31] |
| DBF conversion cost                  | Constant                                       | 5,000         | IDR/l       |          |              |
| By-products revenues                 | Constant                                       | 1,000         | IDR/l       |          | Assumption for seed cake revenue |
|                                      |                                               |               |             |          |              |

#### 4.2. Scenarios design

The model simulations applied scenarios for the different magnitude of future vision to see how the systems respond to a change in future vision, and hence Sumba liquid fuel self-sufficiency (SLF), Sumba GRDP increases from DBF-related revenues (SGI), and national foreign exchange savings (FES). SU is a variable of the political aspect, while SLF, SGI, and FES are related to economic performance. Besides for SLF and SGI, the dynamics of some related variables were simulated: the sense of urgency (SU), technology technical readiness (TR), Sumba developed marginal land area (MD), Sumba oilseeds feedstock, and Sumba DBF production ($r_{DC}$).

The reference mode is the condition of “full pressure” where future vision is absent. Three vision scenarios were set:
- “full vision” (FV) which is a contrast to reference mode,
- “medium vision” (MV), and
- “low vision” (LV).
Future vision value is a combination of weight to vision (WVS) and future vision power (FVS) (Table 2).

**Table 2. Design of vision scenarios.**

| Scenario                          | Weight to vision (WVS) | Future vision power (FVS) |
|-----------------------------------|------------------------|---------------------------|
| Reference Mode / Full Pressure (FP)| 0                      | 0                         |
| Full Vision (FV)                  | 1                      | 1                         |
| Medium Vision (MV)                | 0.5                    | 0.7                       |
| Low Vision (LV)                   | 0.5                    | 0.1                       |

5. Results and Discussion

The reference mode defines the problem where SU is fully driven by pressure. Resulting from reference mode simulations (Figure 3), the SU profile drives TR to allow it to be completed by 2028 with commercialization realized in 2031. The SU profile drives marginal land development in 2027 so that the sufficient feedstock volume to run a DBF plant can first be harvested in 2031. Thus, DBF production is expected to commence in 2034 and then bring 100% liquid fuel self-sufficiency to Sumba by 2039 when SGI achieves USD 198 million. The SGI then peaks at USD 289 million in 2043.

![Figure 3. Dynamics of liquid fuel self-sufficiency, GRDP increase from DBF-related revenues, and relevant indicators for Reference Mode.](image)

5.1. Implication across vision scenarios

The scenarios were assessed by applying planting delay, liquid fuel self-sufficiency, Sumba GRDP, and national FES. These indicators are determined by the dynamics of each stage driven by SU.

The modeling results (Figure 4) show that in reducing liquid fuel demand through the proposed strategy, SU is the key leverage point which is significantly affected by the future vision.
At the reference mode where future vision is absent, SU fluctuates the most. An increase in future vision at the same WVS increases SU which in turn improves the progress of technology readiness, marginal land development, oilseeds feedstock production, and DBF production.

Thus, in increasing liquid fuel self-sufficiency and hence GRDP of Sumba, the pressure should be minimized, while the future vision should be maximized and maintained high.

**Figure 4.** Dynamics of Sumba DBF production across the full (FV), medium (MV), and low (LV) vision scenarios.
Table 3 shows implications of future vision in planting delay. Planting delay at full vision (FV) scenario is three years, while at medium (MV) and low (LV) vision scenarios it is eight and fourteen years respectively which are significantly longer.

It is interesting that FP and MV result in a similar planting delay. This is resulted by given assumptions that generate SU through pressure from BOT, such as oil price and liquid fuel supply and demand volumes.

### Table 3. Implications across the full (FV), medium (MV), and low (LV) vision scenarios for a range of variables.

| Parameters                                                   | Reference Mode / Full Pressure (FP) Scenario | Full vision (FV) scenario | Medium vision (MV) scenario | Low vision (LV) scenario |
|--------------------------------------------------------------|---------------------------------------------|---------------------------|-----------------------------|--------------------------|
| Weight to vision (WVS)                                       | 0                                           | 1                         | 0.5                         | 0.5                      |
| Future vision power (FVS)                                    | 0                                           | 1                         | 0.7                         | 0.1                      |
| Year when conversion technology ready (TR)                   | 2028                                        | 2023                      | 2026                        | 2030                     |
| Desirable year of planting (year when TR of full vision completed - cultivation time before first harvest = A) | 2020                                        | 2020                      | 2020                        | 2020                     |
| Year of starting marginal land area development               | 2027                                        | 2023                      | 2027                        | 2032                     |
| Year of first harvest of oilseed feedstock                   | 2031                                        | 2026                      | 2031                        | 2037                     |
| Actual year of planting (year of feedstock first harvest - cultivation time before first harvest = B) | 2028                                        | 2023                      | 2028                        | 2034                     |
| Year of starting DBF production from feedstock grown on marginal land | 2034                                        | 2030                      | 2035                        | 2040                     |
| Planting delay (towards expected time to TR at full vision = B – A) | 8 yrs                                       | 3 yrs                     | 8 yrs                       | 14 yrs                   |

Figure 5 shows the dynamics of SU, SLF, GRDP increases, and FES across scenarios. The reference mode produces the most fluctuated SU, which becomes more stable by applying a higher future vision. At full vision (FV) scenario, SU profile allows the first harvest of feedstock in 2026 and then DBF production in 2030, four years earlier than the reference mode. This rate can bring full SLF by 2033 or six years faster than the reference mode. At MV, full SLF is reached by 2039 or six years later than FV, while at LV it did not become full until 2045.

At FV, SU profile allows GRDP to increase from DBF-related revenues reaches USD 289 million by 2041 which exceeds current GRDP. At MV, it peaks at USD 289 million by 2043 or two years later than FV, while at LV it does not even peak by 2045.

SU profile at FV allows FES to reach USD 13.46 billion by 2041. At MV, it peaks at USD 13.46 billion by 2043 or two years later than FV, while at LV it does not even peak by 2045.

An increase in future vision power (FVS) improves liquid fuel self-sufficiency, GRDP increase, and national FES. It is interesting that the performance at reference mode is between medium (MV) and full
(FV) vision scenarios. This results from the SU profile generated by the pressure from BOT. The same urgency level will result in higher performance when the future vision is higher.

![Figure 5](image1.png)

**Figure 5.** Selected indicators across the full (FV), medium (MV), and low (LV) vision scenarios.

### 5.2. Limitations and recommendation for further research
The model has been developed to meet the research aim, yet limitations still exist mainly due to time constraints and participants’ availability. This provides opportunities for model improvement through further works such as:

- exploring further around SU structure, for example, investigating factors other than BOT that drives SU;
- calculating BOT that affects SU profile more representatively;
- performing an analysis of sensitivity to oil price which is the main factor of oil imports value, although this is not critical as BOT is inherently fluctuating and highly uncertain that a future vision is needed to improve SU;
- describing dynamics of TR more accurately by dividing TR into several phases;
- building the function of effects to differentiate between the influence of SU to TR progress rate and SU to marginal land development rate;
- calculating national parameters that consider marginal land area by disaggregating islands that include islands outside of Sumba;
• considering marginal land feedstock management that would affect feedstock productivity and price;
• improving the accuracy of DBF production model by disaggregating several DBF plant units;
• determining DBF production cost more representatively, such as by applying a wide range of by-product revenues and inclusion of transportation cost;
• improving GRDP model by considering multiplier effects on the local economy;
• presenting the dynamics of liquid fuel supply and demand more representatively, by modeling the transition from oxygenated biofuel to drop-in biofuel (DBF) production, also useful in planning for investments;
• simulating the effect of SU on biofuel consumption, to understand better the biofuel demand that affects BOT;
• improving validation, such as by:
  o conducting further direct structure tests that involve experts from a wider area; and
  o improving variable quantifications, especially in modeling the marginal land preparedness.

6. Conclusions
This study has provided a better understanding of how the implementation of marginal land use and biofuel technology innovation needs to be implemented as an integrated strategy to increase liquid fuel self-sufficiency.

The modeling showed that there is an inter-relationship between biofuel development and a sense of urgency (SU) by the highest-level political authority in executing such cross-sectoral strategy. It showed that SU can be increased and sustained by empowering a future vision for the nation. This is important knowledge in improving biofuel development by empowering its political sustainability dimension.

The simulation results show that given a maximum future vision over time, through DBF production from marginal land feedstock, Sumba can achieve full liquid fuel self-sufficiency by 2033. This would make the GRDP increased from DBF-related revenues to exceed the current total GRDP.

This study provided policy recommendations in producing DBF from marginal land-based feedstock by:
• applying maximum future vision all the time in maintaining a high level of SU to minimize the delay and hence maximizing liquid fuel self-sufficiency, Sumba GRDP, and national FES.
• actualizing the future vision in setting apart investment in DBF technology and giving early instruction in planting energy crops on marginal land.
• providing specific supports which are SU-driven, such as:
  o in DBF utilization: DBF pricing through direct subsidy.
  o for marginal land development: supports on infrastructure readiness, local government commitment, landowners willing to cultivate, and land status clarity.

Appendix
Timeseries values for the variables in Table 1
Gas_export_volume [billion cubic feet/yr]:
(2018.00, 900), (2019.00, 800), (2020.00, 750), (2021.00, 600), (2022.00, 600), (2023.00, 400), (2024.00, 300), (2025.00, 300), (2026.00, 250), (2027.00, 225), (2028.00, 200), (2029.00, 175), (2030.00, 150), (2031.00, 125), (2032.00, 100), (2033.00, 75), (2034.00, 50), (2035.00, 25), (2036.00, 0), (2037.00, 0), (2038.00, 0), (2039.00, 0), (2040.00, 0), (2041.00, 0), (2042.00, 0), (2043.00, 0), (2044.00, 0), (2045.00, 0)
Crude_oil_export_volume [bbl/yr]:
(2018.00, 80000000), (2019.00, 76000000), (2020.00, 72000000), (2021.00, 68000000), (2022.00, 64000000), (2023.00, 60000000), (2024.00, 56000000), (2025.00, 52000000), (2026.00, 48000000), (2027.00, 43000000), (2028.00, 39000000), (2029.00, 35000000), (2030.00, 31000000), (2031.00, 27000000), (2032.00, 23000000), (2033.00, 19000000), (2034.00, 15000000), (2035.00, 50000000),
(2036.00, 0), (2037.00, 0), (2038.00, 0), (2039.00, 0), (2040.00, 0), (2041.00, 0), (2042.00, 0),
(2043.00, 0), (2044.00, 0), (2045.00, 0)

Non_oil_&_gas_export_value [USD/yr]:
(2018.00, 2041.00, 2.1e+08), (2019.00, 2.1e+08), (2020.00, 2.1e+08), (2021.00, 2.1e+08),
(2022.00, 2.1e+08), (2023.00, 2.1e+08), (2024.00, 2.1e+08), (2025.00, 2.1e+08),
(2026.00, 2.1e+08), (2027.00, 2.1e+08), (2028.00, 2.1e+08), (2029.00, 2.1e+08),
(2030.00, 2.1e+08), (2031.00, 2.1e+08), (2032.00, 2.1e+08), (2033.00, 2.1e+08),
(2034.00, 2.1e+08), (2035.00, 2.1e+08), (2036.00, 2.1e+08), (2037.00, 2.1e+08),
(2038.00, 2.1e+08), (2039.00, 2.1e+08), (2040.00, 2.1e+08), (2041.00, 2.1e+08),
(2042.00, 2.1e+08), (2043.00, 2.1e+08), (2044.00, 2.1e+08), (2045.00, 2.1e+08)

LPG_import_demand_volume [bbl/yr]:
(2018.00, 175000000), (2019.00, 1.9e+08), (2020.00, 2.2e+08), (2021.00, 2.5e+08),
(2022.00, 2.8e+08), (2023.00, 3.1e+08), (2024.00, 3.4e+08), (2025.00, 3.7e+08),
(2026.00, 4.0e+08), (2027.00, 4.3e+08), (2028.00, 4.6e+08), (2029.00, 4.9e+08),
(2030.00, 5.3e+08), (2031.00, 5.7e+08), (2032.00, 6.1e+08), (2033.00, 6.5e+08),
(2034.00, 6.9e+08), (2035.00, 7.3e+08), (2036.00, 7.7e+08), (2037.00, 8.1e+08),
(2038.00, 8.5e+08), (2039.00, 8.9e+08), (2040.00, 9.3e+08), (2041.00, 9.7e+08),
(2042.00, 1.0e+09), (2044.00, 1.1e+09), (2045.00, 1.2e+09)

Gas_import_volume [billion cubic feet/yr]:
(2018.00, 0), (2019.00, 0), (2020.00, 0), (2021.00, 0), (2022.00, 0), (2023.00, 0), (2024.00, 25),
(2025.00, 50), (2026.00, 100), (2027.00, 200), (2028.00, 400), (2029.00, 500), (2030.00, 700),
(2031.00, 800), (2032.00, 900), (2033.00, 1000), (2035.00, 1100), (2036.00, 1300), (2037.00, 1700),
(2038.00, 1900), (2039.00, 2000), (2040.00, 2200), (2041.00, 2300), (2042.00, 2500),
(2043.00, 3000), (2044.00, 3500), (2045.00, 3800)

Oil_price [USD/barrel]:
(2018.00, 65.0), (2019.00, 66.7), (2020.00, 66.4), (2021.00, 67.1), (2022.00, 67.9), (2023.00, 68.6),
(2024.00, 69.3), (2025.00, 70.0), (2026.00, 70.0), (2027.00, 70.0), (2028.00, 70.0), (2029.00, 70.0),
(2030.00, 70.0), (2031.00, 69.0), (2032.00, 68.0), (2033.00, 67.0), (2034.00, 66.0), (2035.00, 65.0),
(2036.00, 65.0), (2037.00, 65.0), (2038.00, 65.0), (2039.00, 65.0), (2040.00, 65.0), (2041.00, 65.0),
(2042.00, 65.0), (2043.00, 65.0), (2044.00, 65.0), (2045.00, 65.0)

Gas_price [USD/MMBtu]:
(2018.00, 8.80), (2019.00, 8.90), (2020.00, 9.10), (2021.00, 9.30), (2022.00, 9.40), (2023.00, 9.60),
(2024.00, 9.70), (2025.00, 9.90), (2026.00, 9.90), (2027.00, 9.90), (2028.00, 10.00), (2029.00, 10.00),
(2030.00, 10.00), (2031.00, 9.90), (2032.00, 9.80), (2033.00, 9.70), (2034.00, 9.70), (2035.00, 9.60),
(2036.00, 9.60), (2037.00, 9.60), (2038.00, 9.60), (2039.00, 9.60), (2040.00, 9.60), (2041.00, 9.60),
(2042.00, 9.60), (2043.00, 9.60), (2044.00, 9.60), (2045.00, 9.60)
(2036.00, 9.50), (2037.00, 9.40), (2038.00, 9.30), (2039.00, 9.20), (2040.00, 9.10), (2041.00, 9.00),
(2042.00, 9.00), (2043.00, 8.90), (2044.00, 8.80), (2045.00, 8.70)
Palm oil price [USD/t]:
(2018.00, 490), (2019.00, 500), (2020.00, 500), (2021.00, 510), (2022.00, 510), (2023.00, 520),
(2024.00, 520), (2025.00, 550), (2026.00, 550), (2027.00, 560), (2028.00, 560), (2029.00, 560),
(2030.00, 560), (2031.00, 560), (2032.00, 560), (2033.00, 570), (2034.00, 580), (2035.00, 590),
(2036.00, 590), (2037.00, 600), (2038.00, 610), (2039.00, 620), (2040.00, 620), (2041.00, 620),
(2042.00, 620), (2043.00, 620), (2044.00, 640), (2045.00, 640)
Sumba_liquid_fuel_demand [kl/yr]:
(2018.00, 91595), (2019.00, 96175), (2020.00, 100983), (2021.00, 106033), (2022.00, 111334),
(2023.00, 116901), (2024.00, 122746), (2025.00, 128883), (2026.00, 135327), (2027.00, 142094),
(2028.00, 149198), (2029.00, 156658), (2030.00, 164491), (2031.00, 172716), (2032.00, 181352),
(2033.00, 190419), (2034.00, 199937), (2035.00, 209937), (2036.00, 220434), (2037.00, 231456),
(2038.00, 243029), (2039.00, 255180), (2040.00, 267939), (2041.00, 281336), (2042.00, 295403),
(2043.00, 310173), (2044.00, 325681), (2045.00, 341966)
National_liquid_fuel_demand [kl/yr]:
(2018.00, 7.5e+07), (2019.00, 7.5e+07), (2020.00, 8e+07), (2021.00, 8.6e+07), (2022.00, 9.2e+07),
(2023.00, 9.7e+07), (2024.00, 1.03e+08), (2025.00, 1.09e+08), (2026.00, 1.15e+08), (2027.00, 1.21e+08),
(2028.00, 1.27e+08), (2029.00, 1.33e+08), (2030.00, 1.38e+08), (2031.00, 1.44e+08), (2032.00, 1.5e+08),
(2033.00, 1.58e+08), (2034.00, 1.67e+08), (2035.00, 1.75e+08), (2036.00, 1.84e+08), (2037.00, 1.92e+08),
(2038.00, 2.01e+08), (2039.00, 2.09e+08), (2040.00, 2.2e+08), (2041.00, 2.28e+08), (2042.00, 2.36e+08),
(2043.00, 2.44e+08), (2044.00, 2.52e+08), (2045.00, 2.6e+08)
National_oil_fuels_production [kl/yr]:
(2018.00, 4.5e+07), (2019.00, 4.5e+07), (2020.00, 4.5e+07), (2021.00, 5e+07), (2022.00, 5e+07),
(2023.00, 5.5e+07), (2024.00, 6e+07), (2025.00, 6.5e+07), (2026.00, 8e+07), (2027.00, 8.5e+07),
(2028.00, 9e+07), (2029.00, 9.5e+07), (2030.00, 1e+08), (2031.00, 1e+08), (2032.00, 1e+08),
(2033.00, 1.05e+08), (2034.00, 1.05e+08), (2035.00, 1.1e+08), (2036.00, 1.1e+08), (2037.00, 1.15e+08),
(2038.00, 1.2e+08), (2039.00, 1.2e+08), (2040.00, 1.25e+08), (2041.00, 1.25e+08),
(2042.00, 1.25e+08), (2043.00, 1.3e+08), (2044.00, 1.3e+08), (2045.00, 1.35e+08)
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