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DYNAMIC ASSESSMENT OF THE SUSTAINABILITY OF ALGAL BIOREFINERIES IN THE PRODUCTION OF BIOFUELS

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ABSTRACT

Barriers exist against the emergence of any new technology. For algal biorefineries, these barriers manifest in competition for resources, slow capacity growth, and the diminishing urgency of environmental issues, which worsen as the algae-based biofuel is diffused. Given the dynamic nature of the problem, a system dynamics model is developed with the objective of identifying areas for intervention that can promote diffusion with minimal negative feedback. The model contains four dynamic hypotheses, representing areas that hamper the diffusion of algae-based biofuel. These hypotheses are the economic, social, and environmental sectors that are affected by the operations of algal biorefineries. A sensitivity analysis of parameters revealed the strategies which ensured the successful propagation of the technology relied on good anticipation of market growth and the maximized energy yield growth from investments. This was compared to traditional solutions such as incentives for adoption and penalties against emissions, and linear models. The results indicated that the linear models failed to capture the dynamicism of the problem. The contribution of this study is a new perspective on managing the growth of algal biorefineries.

Keywords: Renewable Energy, Algal biorefinery, Biofuels, Energy systems, System dynamics, Technology acceptance

1. PROBLEM BACKGROUND

Microalgae are a promising replacement for conventional sources of fuel due to its ease of cultivation, minimal fresh water usage, and ability to remove carbon dioxide from the atmosphere, among other advantages pertinent to major environmental problems [1]. Yet, there are still numerous barriers against the transition to this source of energy.

Much research has been invested in improving the operating parameters of algal biorefineries [2]. What remains to be addressed are the problems resulting from harmful feedbacks caused by the diffusion of the technology itself. These include problems such as resource competition and capacity shortage, which grow as the biofuel is diffused [3], [4].

To manage the growth of algal biorefineries, a system dynamics model is proposed. This allows for the feedback relationships that exist between the biorefinery, and its social, economic and environmental landscape, to be considered. The purpose of this approach is to develop policies towards the strategic diffusion of the biofuel, promoting consistent growth and lacking negative repercussions in the long-term. In this way, the study demonstrates a dynamic perspective towards sustainability and policy-making.

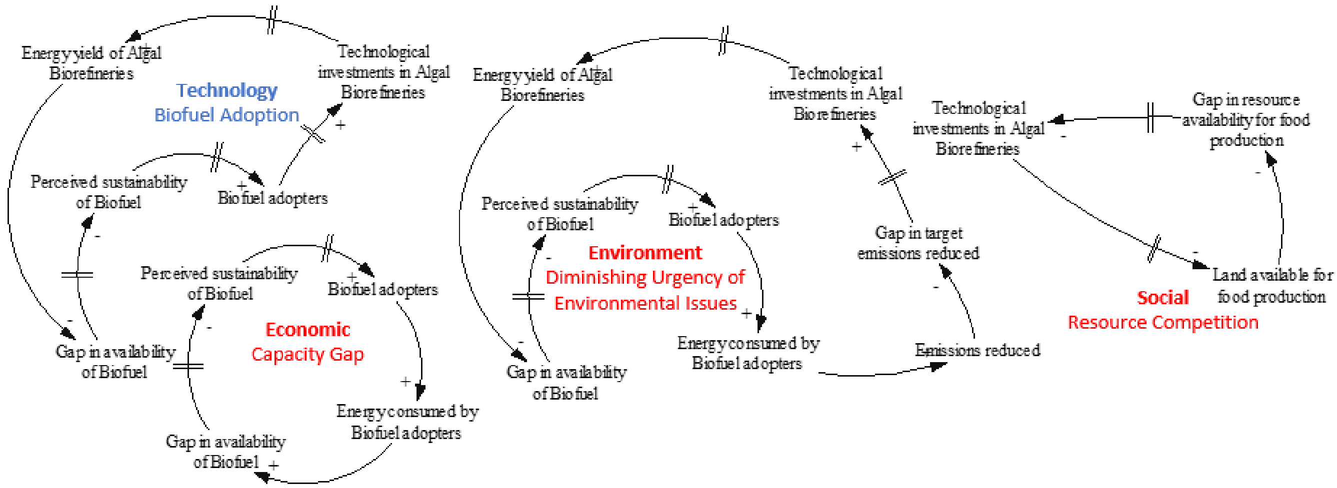

Fig 1 Disaggregated Feedback Loops on Adoption of Biofuels.

2. MODEL DEVELOPMENT

For emerging technologies, one major barrier to diffusion is the awareness of risks, which will increase as more users test the technology [5]. Algal-based energy is generally robust against most major threats due to its resistance against contamination and remediating properties. Its main source of risk is the availability of capacity to replace the demand for the biofuels, particularly when the rate of diffusion is strong. The perception that the capacity of new energy systems is insufficient can prove to be more damaging to acceptance than high costs [4]. This is a potential consequence when the growth rate of demand exceeds that of the capacity. As energy production from open-pond systems can be unstable, and the cost to establish enclosed photobioreactor systems is high, lack of capacity is a major threat for algal biorefineries [1]. These feedback relationships for capacity growth and energy consumption are described in the Technological and Economic sectors in Fig. 1.

As problems are resolved, pressure to address them diminish. This leads to decelerated growth and potentially allows for backsliding. In the case of [6], pressure for economic growth initially spurred the adoption of new technologies but was insufficient to sustain adoption as time progressed. In algal biorefineries, similar patterns may be observed in the treatment of environmental issues. The appeal of biofuels lies in the absence of emissions, as compared to conventional fuels. Its application would thus resolve the problem, and also remove the incentive for further investment. This feedback relationship is described in the Environment sector in Fig. 1.

The cultivation of algae with biofuels shares many resources with agriculture, including land and water. This is true for most biofuels, although microalgae are relatively more efficient because of lesser space requirements and higher yield [1]. Nonetheless, in specific areas, competition for resources in specific areas can raise food prices and affect commercial operations at a local level [7]. Depending on the local scenario, competition for resources may suppress capacity growth. This brings to light the importance of site selection in the establishment of energy systems [8]. The feedback relationship between capacity growth and resource availability is represented by the Social sector in Fig. 1.

These feedback relationships represent hindrances to the growth of biofuels. Specifically, these stunt the growth of adoption of this technology by institutions and industries that can make use of it. Technological investments may also be expected to decline as a result of these feedbacks. A descriptive reference mode is drawn based on these behaviors (see Fig. 2).

Using Vensim PLE software, a simulation model was developed to test the validity of the feedback relationships. The simulation model used simple mathematical equations to describe the relationships between these variables, and parameters to represent the weights of these relationships. An example of these equations is demonstrated through a stock variable, *technological investments in algal biorefineries* ($TIAB_t$). This changes according to three components: namely the *gap in target emissions reduced* (GTE_t), the amount of *biofuel adopters* (BA_t), and the *gap in availability of biofuel* (GAB_t). Each component is affected by a parameter representing the unit contribution of each variable (respectively u_{GTE}, u_{BA} and u_{GAB}).

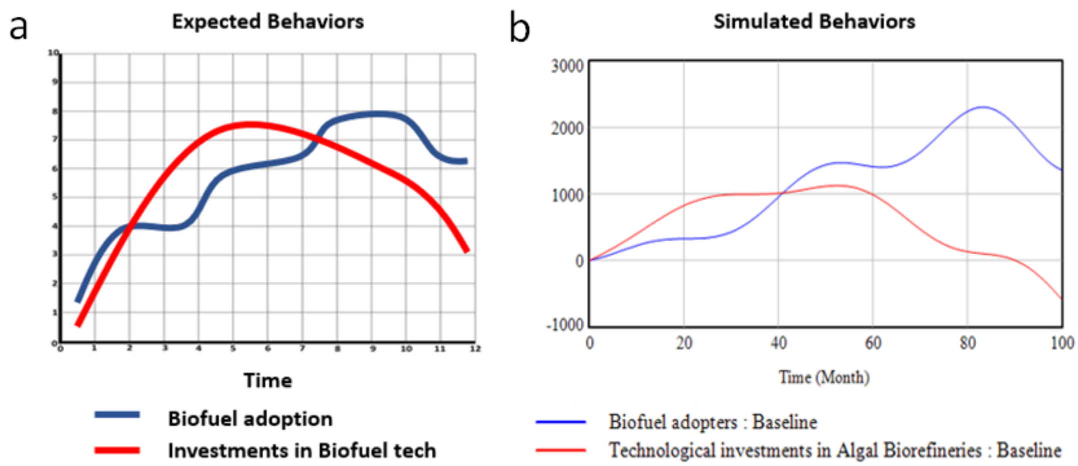

Fig 2 Comparison of (a) expected behaviors and (b) simulated behaviors.

$$TIAB_t = TIAB_{t-1} + \Delta TIAB_t \qquad (1)$$

$$\Delta TIAB_t = GTE_t * u_{GTE} + BA_t * u_{BA} + GAB_t * u_{GAB} \qquad (2)$$

3. SIMULATION AND SENSITIVITY ANALYSIS

The simulation model was validated by comparing the reference mode with the simulated behaviors. The side-by-side comparison depicted in Fig. 2 is an evidence to support the validity of the feedback relationships derived from literature, in stifling the diffusion of the biofuel.

Sensitivity analysis was conducted to determine the effective areas for simulation on the parameters of the model wherein one parameter was altered at a time. Three cases were compared together: a baseline, a case where the parameter value is 50% higher, and a case where it is 50% lower. Based on this, the parameters with the strongest potential of achieving the desired effect are (1) unit increase in investment per additional adopter (u_{BA}) and (2) the unit increase in energy yield per additional unit investment (u_{GE}). When increased, both of these parameters proved to be capable of breaking the cycle of growth and stagnation.

Based on the sensitivity analysis on u_{BA} (see Fig. 3), it is suggested to anticipate the growth in demand. This goes against the poor scalability and high investment required in establish algal biorefineries. Given that global climate finance favors "short-termism", it is unlikely that this policy is being implemented [9]. Yet, it is evident that the overall cost of failed investments and continuous search for new technologies would exceed the costs associated with uncertainty and long payback periods. The results of encouraging further investment, along with the applicability of algae-based biofuel for large-scale production [1], encourage further investment for the sustainability of economic and environmental gains.

The results of the sensitivity analysis on u_{GE} are aligned with the previous analysis on the unit increase in investment (see Fig. 4). In cases where no additional funds are available, it appears that streamlining the research and development process for agile is equally beneficial to additional investments. This way more gains can be derived from each unit investment.

For comparison, common strategies for emerging energy technologies were also tested. Some countries implement carbon trading as a way to encourage manufacturers to keep their carbon emission within a certain threshold [10]. In this model, this may be incorporated as the unit conversion of the gap between emission reduction goals to investments for expansion. More costs would be incurred from poor performance according to the environmental goals. While this is a logical solution, a sensitivity analysis of this parameter

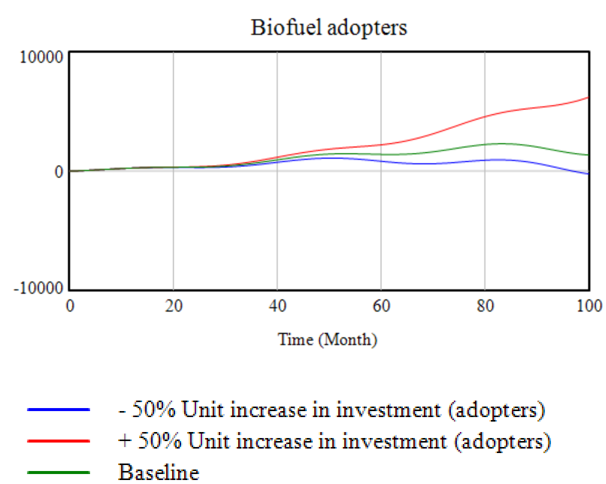

Fig 3 Sensitivity to unit increase owed to adopters.

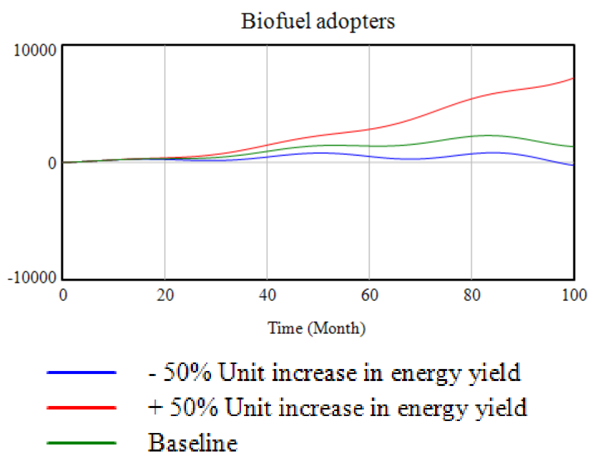

Fig 4 Sensitivity to unit increase in energy yield.

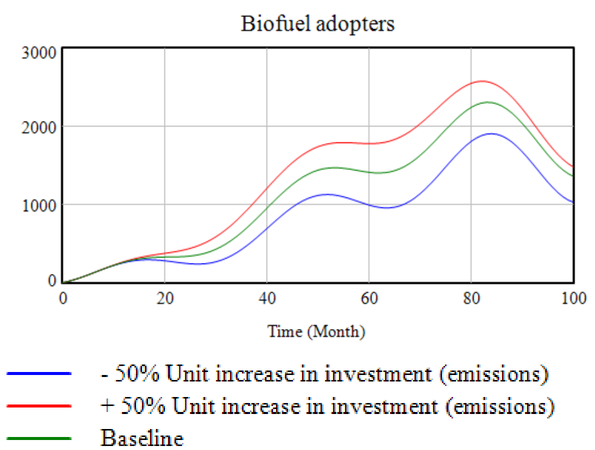

Fig 5 Sensitivity to unit increase in investment owed to environmental goals.

reveals that the benefits that can be derived from this policy are short term (see Fig. 5). Adoption is marginally higher when the incentives are raised, yet the general trend remains the same as the baseline, showing no lasting improvement.

4. CONCLUSIONS

In this study, hypothetical feedback relationships were simulated to determine if these were legitimate barriers against the propagation of algal-based biofuels.

From the simulation and sensitivity analysis that was conducted, two policies may be derived. First, investment in anticipation of growth is recommended; and second, streamlining yield growth that can be derived from the investments can have the same benefit. Future studies may seek to develop these solution concepts into concrete policies. Among the potential extensions are an investment model for the growth of the algal biorefinery, and applying project management frameworks on research and development in streamlining downstream processing.

As neither of the suggested policies addresses the resource competition, further study may also be done either in maximizing usage efficiency of the shared resource on the part of algae cultivation or in the industries, it is competing with for this resource.

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