

Criteria prioritization for sustainable development of second-generation bioethanol in Thailand with an application of Delphi-AHP technique

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8

9 Abstract

10 Background:

11 The availability of underexploited agricultural residues in Thailand opens up the opportunity to supply second-generation
12 bioethanol production. The national implementation of residues-to-biofuel can potentially initiate the bioeconomy and
13 greenhouse gas mitigation, requiring engagement from the multi-stakeholders to develop effective policy recommendations.
14 Thus, the study aims to optimize the implementation of the national strategy from a multi-criteria approach to evaluate the
15 concerned aspects and important indicators for second-generation bioethanol development through a participatory
16 prioritization by the actual stakeholders

17 Methods:

18 To analyze the relevance of the different dimensions regarding important levels of criteria, a Delphi-AHP technique was
19 applied. The evaluation process was conducted with different stakeholders and elaborated by using a pairwise comparison of
20 4 dimensions (main-criteria) and 12 indicators (sub-criteria). The evaluation was applied to the participants to share their
21 preferences evaluating the most important factors from the aspect of technical feasibility, environmental impacts, economic
22 feasibility and social impacts.

23 Results:

24 Bioethanol stakeholders in Thailand from 5 different branches (industry/ business sectors, NPO/NGO, governmental sectors,
25 academic/research institute and financial institution/bank) participated in the Delphi survey. The 20 expert's evaluation of four
26 dimensions reveals the highest score from the economic feasibility (32.3%), followed by environmental impacts (25.6%),
27 technical feasibility (24.0%) and social impacts (18.1%). From the sub-criteria assessment, the participants selected 'final price
28 per liter', 'added value of input materials' and 'net energy balance' for the top three important indicators among 12 sub-criteria.
29 From the identification of connection between preferable criteria and participants' expertise, the results encouraged the

1 process of employing different associated backgrounds into account at the step of policy planning in addition to the
2 consideration of affiliations.

3 **Conclusions:**

4 The stakeholder's participatory evaluation indicated the importance of economic aspects, highlighting the necessity of the
5 governmental driven policy that needs to be considered. However, implementation scenarios have to be embedded in a
6 broader range of aspects because all the dimension were rated with high impacts. For the future sustainable bioenergy,
7 involvement from stakeholders' opinions can imply multifaceted scenarios that may interconnect to the social acceptance and
8 benefits for all relevant players when considering the development of advanced bioenergy as a policy recommendation.

9

10 **Keywords**

11 Second-generation bioethanol, stakeholder's perception, Delphi-AHP technique, participatory criteria prioritization

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1 Introduction

2 The greenhouse gas (GHG) reduction goal is an urgent driver for Thailand to search for sustainable energy sources to pursue
3 effective mitigation. Thailand has committed to the Paris Agreement at the COP21 meeting to reduce 20-25% GHG intensity
4 from the business as usual by 2030 [1, 2]. Constantly increasing energy demand leads to the requirement of a sustainable energy
5 transition to stay within the greenhouse gas emission budget. Taking an opportunity from agricultural products in the country,
6 Thailand attempts to substitute the consumption of fossil fuels with bioenergy production from the agricultural crops. At
7 present, bioenergy production in Thailand comprises bioethanol and biodiesel. In particular, for bioethanol production, cassavas
8 and sugarcanes are cultivated to serve the biofuel supply in the transportation sector. According to the long-term promotion of
9 bioethanol, supported by the Alternative Energy Development Plan (AEDP 2015), the production goal in 2036 is aimed to be
10 4,136 million liters [3], increasing from production in 2019 by 157% [4].

11 This conventional bioethanol development thus far benefits on the abatement of dependency on fossil fuel. However, there
12 are challenges that need to pay attention to while biofuel production becomes intensified in proportions. The controversial
13 issues involve the production process, as the projected goal of ethanol production could associate with higher requirement of
14 crops cultivation. Due to a limit of yield per area up until now, the national policy to promote bioethanol for substitution of
15 fossil fuel is projected for a land use expansion [5–7], which also affects land use of food and other crops cultivation [6]. In
16 this sense, the conflict between the crops supply and increasing bioethanol demand needs to be taken into consideration to
17 achieve a sustainable long-term bioethanol policy in Thailand.

18 Nowadays, sustainability for future bioenergy development has been scrutinized extensively. Although the conventional
19 production of biofuel has admittedly provided the benefits of fossil fuel replacement, the widespread commercialization of the
20 biofuel industry from the past decades has been inevitably associated with the environmental side-effects, involving conflicts
21 of land use for food-based crops cultivation [8–10]. The recent researchers and stakeholders have paid more attention to pursue
22 the transition of bio-based products or bioenergy systems towards sustainable direction by addressing indicators from holistic
23 points of view based on United Nations Sustainable Development Goals (SDGs) [11–13]. The exemplary framework can be
24 observed from the policy by European Union (EU), which has shown more concerns on sustainability and environmental
25 harmonization for biofuels and bioliquids implementation [8].

26 Towards the direction of sustainability, one of the implementable concepts is the utilization of the regional biomass, such
27 as wood-based wastes, to supplying as bio-materials [14–16]. The strategy would not only provide the environmental and
28 economic advantages, but the investment in bio-based industries is also expected to contribute to social benefits, such as
29 increasing workforce from the local business, educational opportunities, and research projects for enhancing innovation [12,
30 17, 18].

31 Under the debate of sustainable resource use, the energy sector is considered as one of the potential cascading use of
32 agricultural residues to enhance values of agricultural industries in the form of bioenergy [19]. Particularly, the bioenergy from

1 lignocellulosic biomass showed the advantages in fostering the utilization of agricultural wastes, saving land use along with
2 socio-economic benefits, such as food security [20]. In Thailand, there are agricultural residues generating and being left unused
3 in the farm areas distributed across the country. The regional availability of biomass provides an opportunity for Thailand to
4 make use in the production of higher-value products. The agricultural residues have been found to have an excessive amount
5 from the plantation of the major crops, such as rice, sugarcanes, cassavas, and palms [21]. Nonetheless, the practical
6 applications of agricultural residues are limited to only the primary utilization, such as animal feed, fertilizer, and raw material
7 for electric power plants [22–25].

8 Behind this background, the dimensions for a successful implementation of second-generation bioethanol in Thailand are
9 anticipated to be manifold. Apart from the biofuel as energy supply, which can support the concept of controlling land use
10 expansion, the utilization of leftover lignocellulosic materials could be projected to mitigate the environmental impacts from
11 the open field burning issue [26, 27]. In addition to that, the utilization of agricultural residues would provide the possibility of
12 longer value chains of biorefinery production, which also plays an essential role in bioeconomy concept [28, 29], generating
13 direct and indirect socio-economic benefits [12, 30, 31].

14 Although the conversion of lignocellulosic biomass to bioethanol has been developed to the pilot level [28], it can be stated
15 that the concept of utilizing agricultural residues for biofuel purposes has never been proposed to the stakeholders or put into
16 consideration at the policy making level. In order to promote the commercialization of second-generation ethanol for the
17 sustainable bioenergy framework, the important elements would involve decision-making based on different backgrounds and
18 complexity of stakeholders. It is nearly impossible to solely take the factor of technological feasibility into account, as the
19 production chain consists of several industrial and service branches such as agricultural, logistics, and at times many production
20 facilities [32].

21 In the process of energy planning, aside from techno-economic feasibility, the estimation of social and environmental
22 impacts has become a vital concern to evaluate for the most sustainable system [33]. The system optimization from an
23 environmental perspective is necessary to be accounted; however, it may in turn cause the conflict with technical or economic
24 development [34, 35]. Therefore, instead of approaching with only single dimension, which may lead the decision-making to
25 be coupled with risks, conflicts, and tradeoffs [36], the impact of multi-dimensional attributes are necessary to be evaluated
26 and selected from the actual awareness and concerns from stakeholder's perception.

27 Even though numerous studies have conducted multi-criteria decision analysis (MCDA) in the field of bioenergy assessment
28 up until the present [35], the evaluation by eliciting the stakeholders' opinions through the participatory assessment under the
29 topic of second-generation bioethanol production in Thailand's context has not been executed. Inducing expert perspectives
30 into system evaluation for the advanced bioethanol production is considered newness from the study.

31

1 **Foreseeable constraints of the first-generation bioethanol implementation in Thailand – Literature review**

2 The promotion of bioethanol development in Thailand contributed the benefits to the transport section since it provided the
3 self-sufficient sources of energy supply. Since 2004, commercialized bioethanol shows a constant growth according to fostering
4 policy for production and consumption sides. Nonetheless, the bioethanol development plan and policy of Thailand, namely
5 the Alternative Energy Development Plan (AEDP, 2015–2036), has barely integrated the socio-economic dimension since it
6 involves crossing-disciplinary fields and authority from governmental organizations. On the contrary of achievement in
7 replacing the fossil fuel, the long-term policy is prone to encounter with constraints occurred due to several aspects, which may
8 become the bottlenecks for the bioethanol development policy in Thailand in the future.

9 According to the study by Chanthawong et al., the multi-criteria evaluation conducted by relevant stakeholders in the biofuel
10 market revealed their perceptions of the current bioethanol policy implication [37]. Although the participants agreed that
11 Thailand’s bioethanol policy advocates energy security in the country, the biofuel promoting approach still lacks the concrete
12 strategy to improve the crops cultivating management for the long-term development goal. Due to the limited farm areas, there
13 is a bottleneck to stabilize the sources for biofuel supply to correspond to the production goal in the future. Along with that,
14 prices of raw material, as well as the production cost are considered significant influences. Since biofuel production mainly
15 varies on the crop price, the fluctuation of the feedstocks price is a worrying issue that the government needs to overcome.

16 From the background of instability in raw materials price, the biofuel pricing mechanism in Thailand is structured by a
17 subsidization system [38]. The stakeholders of bioethanol business projected the opportunity that demand can still grow steadily,
18 as long as there are incentives for driving the demand in terms of blending mandatory, tax reduction or subsidization [37]. The
19 subsidy is collected from the non-bio-based fuel as oil funds. The oil funds are the instrument to stabilize the retail price of
20 bioethanol blended gasoline, which also encourages the consumption of biofuel by maintaining the discount for users of
21 bioethanol blended gasoline type, E20 and E85 (20% and 85% ethanol blending rates, respectively) [38]. Nonetheless, the
22 reliance on governmental subsidization has also been criticized as a cause of distortion of the actual price and a possible long
23 term negative effect to the market [39]. By controlling retail price for consumers, the lower price of gasoline is related to entail
24 the energy consumption to become higher [39, 40].

25 Apart from the issue concerning market mechanism of biofuel, it has been unclear from the policy making regarding the
26 sustainable strategy of bioethanol development. In the study by Lecksiwilai et al., the lack of attention on environmental impacts
27 from the currently imposed policy was emphasized as an urgent topic that needs to be accounted [41], especially the dimension
28 of land use change corresponding to the increasing of agricultural production [6]. The fact that crop yields of sugarcanes and
29 cassavas have not improved significantly in the last decades [42, 43], the tendency of future scenarios is likely to induce the
30 increasing land use for crops cultivation in order to reach the target of ethanol production goal [6, 44]. While the land use
31 change for expanding cultivation areas have to deal with CO₂ extracted from soil carbon stock [6, 45], enhancement of crop
32 yields, which was contemplated as one of possible solutions under the land use restriction, possibly demands higher input

1 fertilizers and pesticides. Consequently, the foreseen limited crops yields would decrease the GHG mitigation effect of the
2 biofuel, resulting in environmental tradeoffs from the life cycle GHG emission [6, 41]. In addition to that, the cultivation of
3 cassavas and sugarcane is associated with intensive water footprint per ton of crop production. It has been investigated that
4 the water footprint in the cassava plantation required double amount of water comparing to sugarcane plantation [46].

5 The complications of current policy also involve a socio-economic aspect. Concerning the traditional practice of sugarcane
6 plantation, the agricultural residues management is executed by field burning [47, 48]. At the end of each cultivating season
7 and before starting the new cultivating round, the preparation steps comprises the sugarcane trash burning. This procedure gives
8 impact to not only the environmental burden, but the health issues of the farm workers also are directly affected, giving
9 disadvantages to the farmers [49]. In particular for the agricultural laboring system, unguaranteed crop prices for stable incomes
10 of the farmers, and unequally protected by national labor law affect the quality of farming job. Thus, several dimensions take
11 part in the bioethanol policy, which are necessary to be evaluated for the long term sustainable development [50].

12 The information from the mentioned studies reflected the existing issues and prospective barriers in the bioethanol policy
13 in Thailand particularly on the feedstocks supply. Exploring a substitution of the conventional feedstocks is recognized as a
14 promising option especially from the available agricultural residues. The utilization of lignocellulosic biomass for second-
15 generation bioethanol have verified the reducing effect of GHG emissions based on ethanol conversion potential [27, 51]. The
16 residues derived from crop plantation showed optimistic future in terms of availability, non-food materials and promising
17 results of GHG reduction [52]. Nonetheless, the assessment from the studies thus far still affirmed that production cost was the
18 imperative constraint that still needs to be tackled for the development to the commercial-scale of advanced biofuel [53–55].

19 From the angle of current biofuel policy, there are many underlying opportunities for the bioethanol development to reach
20 the long-term goal. Towards the process of policy planning for advanced bioethanol development, aside from technical and
21 economic viability, the estimation of social and environmental impacts have become vital concerns to evaluate for the most
22 sustainable system [33]. It is irrefutable to say that to commercialize the advanced biofuel technology, it involves many
23 uncertainties, trans-disciplines, standards and measures as well as the related players, such as the crops growers, private firms,
24 governments and ending products users [35, 56, 57]. Therefore, the proposal of the alternative system of bioethanol should be
25 aware comprehensively from various backgrounds and based on the bottom-up opinions sharing by incorporating multi-
26 disciplinary organizations in the bioethanol value-chain.

28 **Objective of the study**

29 Considering that drawbacks and projected constraints from the current first-generation bioethanol would inevitably occur
30 in the near future, transitioning from the conventional ethanol production to the second-generation technology is a promising
31 solution. For a future sustainable policy, it is necessary to construct the system based on the assessment from the multi-

1 disciplinary aspects. In order to bridge the gap in the transdisciplinary assessment in regard to sustainable framework for policy
2 implications, socio-economic and environmental variables require to take part in the system analysis and decision-making.

3 Thus, the objective of this study is to evaluate the level of importance of criteria from several relevant dimensions by
4 involving the stakeholders' perspectives. The outcomes of criteria prioritization are expected to reflect the most concerned
5 topics and preferences that bioethanol stakeholders encountered at the current stage, which could be beneficial for second-
6 generation bioethanol policy recommendations. The results of criteria prioritization by the stakeholders in this study are planned
7 to be accommodated in the scenarios analysis as a further study step to determine the consensual sustainable strategy for second-
8 generation bioethanol development.

9 Consolidating the different viewpoints from the various branches of stakeholders with the application of Delphi-AHP
10 (Analytic Hierarchy Process) in the context of second-generation biofuel policy in Thailand is considered a novelty. With this
11 approach, the stakeholders are provided the opportunity to share their preferences and concerns which could become a
12 foundation for the second-generation ethanol policy development. In addition, the stakeholders are given chances to rethink the
13 preferences under the consideration of the first survey round. Following the Delphi-AHP procedures, it is expected to enable
14 the policymakers to objectively achieve the efficient and justified indicators in the policy design, since the technique could
15 eliminate the subjective opinions, which might lead to the bias decisions.

16 17 **Methods: Integrated approach of Delphi-AHP**

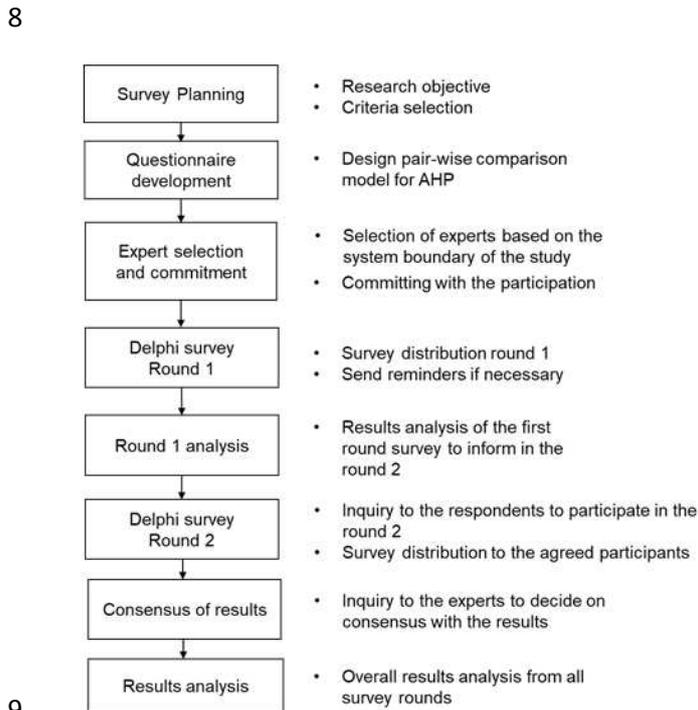
18 AHP, a multi-attribute decision-making method, was initially developed by Saaty, being used broadly in the policy-making
19 process [58]. The application of AHP was verified to be a functional tool for dealing with various indicators and the selection
20 of alternative scenarios for strategic planning [59]. It is categorized as a type of value measurement model that helps decision-
21 makers prioritize their preferences from the alternatives and criteria set through the scoring system by comparing pairwise
22 and giving the weights for levels of importance or preference [58]. This method results in the relative weights of each particular
23 criterion that shares the same goal of the study [60].

24 However, the practical tools of MCDA can also be combined from multiple types to provide dimensions of the study, rather
25 than limited to only one [61]. To achieve a collective decision for policy-making from the stakeholders' perspectives, the
26 current study applied the Delphi technique in the survey conduction. Delphi survey is a useful tool that has been developed for
27 a wide range of areas, for instance, Delphi for upcoming technologies [62, 63], Delphi for policy-making [64], or Delphi for
28 problem-solving [65]. The characteristics of this technique showed the advantage for encouraging the anonymity during the
29 survey conduction without physical assembly. In spite of that, the fundamental feature for the process being used in this study
30 is the transparency of the answers among the participants and the repetition of survey round based on the disclosure to seek the
31 consensus point [66].

1 Process of survey preparation and conduction

2 In this study, Delphi-AHP methods were deployed to prioritize the important aspects and criteria regarding
3 commercialization and policy implications of the second-generation bioethanol in Thailand. The evaluation of important levels
4 of the associated criteria was conducted by the relevant experts. The criteria were addressed from crossing dimensions of a
5 whole supply chain from farm to ethanol production, including technical, environmental, and socio-economic aspects from
6 diverse participants' perspectives.

7 The process flow of the survey and data analysis is summarized in Figure 1.



10 Figure 1 process flow of the current study

11 Survey planning

12 The research question was planned to pursue the objective of the study. The questionnaire was planned to inquire the
13 experts' opinions to vote for the preferable criteria to be considered in the second-generation ethanol development in Thailand.
14 For the initial step, the aspects and criteria set were selected and categorized separately in technical, economic, environmental,
15 and social aspects of assessment by sorting from the literature studies and then were designed to pursue the research objective
16 (see **Objective of the study**).

17

18 Design of the questionnaire

19 Following that, the format of questionnaire was designed to let the respondents rate the important level by pairwise
20 comparing two different indicators based on the AHP pairwise comparison method with 9 levels of important rates [58]. The

1 distributed questionnaire can be referred to in Supplementary material 1. The exemplary questionnaires of criteria comparison
2 are presented in section of the supplementary information. (**Supplementary information**)
3

4 Expert panel design

5 The principle of Delphi-survey for collecting opinions shall be taken place with diverse backgrounds of experts group
6 under the specific topic. Based on that, the selection of panel of participating experts was considered from experiences in the
7 field of bioethanol production and other topics in line with the bioethanol supply chain corresponding to the system boundary
8 of assessment in this study, covering biomass feedstock providers, ethanol producers and energy corporations as bioethanol
9 purchasers. Principally, each specialist does not acknowledge each other in order to avoid interference between respondents.

10 Aiming to structure the panelists from the diverse points of views to obtain the outcomes from different opinions and
11 concerns, the experts were selected from 5 distinctive functionality of organizations, which are 1) governmental sectors, 2)
12 business sectors, 3) non-profit or non-governmental organizations, 4) academic or research institutes and 5) financial
13 institutions and banks. In this study, the systematic selection of the participants was carried out from each background to
14 represent the function of organization as well as the opinions towards bioethanol production in Thailand.

15 In a realistic practice, it is not possible to personally indicate the evaluator in every organization due to the fact that
16 some organizations have the delegation system to allocate the tasks, especially in large-sized enterprises. The delegated experts
17 were internally assigned to deliver the Delphi-survey, meaning that the evaluator was determined to be adequate for
18 representing evaluation in the survey conduction under the justification of the organizational executive level. Nonetheless, it
19 was possible to directly contact the participants in person in some cases, such as the experts in the academic fields.
20

21 Delphi survey rounds and consensus

22 In the first round, the Delphi survey questionnaires were distributed to potential targets. After gathering all evaluated
23 scores from the participants, AHP was applied to weight the criteria for prioritizing the level of importance. The hierarchical
24 structure of the variables in this study was determined based on the calculation procedures, as mentioned in section **Analysis**
25 **of the survey data from AHP method**. In the following step, the results from round one of Delphi-AHP were distributed to
26 the participants. The preliminary compilation of results was informed to the experts to provide the opportunity to participate in
27 the second-round survey. After each round of the survey, the participants were asked to consent to the results or re-evaluate the
28 survey. Considering a principle of Delphi survey, the summary of results from round one would encourage the experts to revise
29 the outcomes of their judgements from the earlier survey round [67].
30

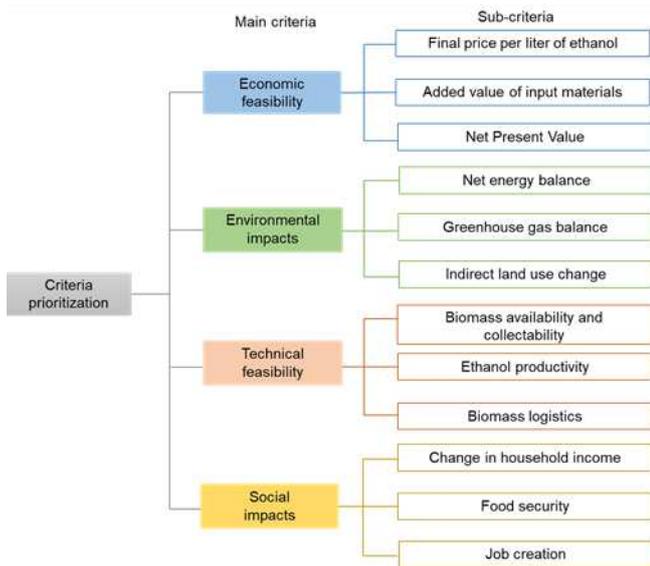
1 **Criteria selection**

2 The criteria in this study were selected from the publications related to the field of energy analysis, as summarized in Table
3 1. The goal is to prioritize the preferable criteria to be focused on the context of second-generation bioethanol. The derived
4 scores of criteria ranking are planned to be undertaken as parameters in the system analysis for proposing the second-generation
5 bioethanol as a policy recommendation.

6 The criteria were selected based on the fundamental that they are independent of one another but eventually correspond to
7 the goal of the study. The scores of criteria evaluations are subjected to contribute in the scenarios study as the further step of
8 the research. The set of criteria relatively affects the results of multi-criteria decision-making outcomes. To achieve the goal in
9 this study, the set of criteria was constituted from technical, environmental, economic, and social aspects. The variables
10 introduced in this study refer to the scope cradle-to-gate, ranging from farm areas to ethanol production as a boundary in this
11 study.

12 The selection of required criteria in this study shares the common ground that they are the quantitative factors, which can
13 be processed in the MCDA. Criteria to be studied were categorized by 4 main aspects of main criteria, comprising 3 sub-criteria
14 under respective aspects, providing a total of 12 sub-criteria to be evaluated. A simple scheme of the hierarchical structure is
15 shown in Figure 2.

16



17
18 Figure 2 Hierarchical structure of selected main criteria and sub-criteria

19

20 Technical feasibility

21 Second-generation bioethanol has been improved for its technical potential as commercialized production has developed
22 in these decades [28]. Nevertheless, the potential of this advanced technology in the context of Thailand has to be verified.
23 First, biomass availability is a criterion for verifying if the capacity of generated agricultural residues is sufficient to be supplied

1 in production units. Moreover, the availability of input materials indicates the potential location for installing facilities and
2 determines the production capacities [68, 69].

3 Next, to verify the potential of input material, ethanol conversion efficiency from the available feedstock needs to be
4 taken into consideration. The ethanol productivity from lignocellulosic materials plays a major part in evaluating cost-benefits
5 [70] since the ethanol conversion efficiency can be deficient due to the constraint from the complex structures of lignocellulosic
6 components [71]. Therefore, conversion process requires more operating cost and input energy compared to the conventional
7 production [53].

8 In regard to the related elements in the production boundary, biomass logistics is one of the key factors for assessing
9 technical feasibility. This factor refers to distances and transferable amounts of biomass from supply area to the ethanol
10 production process and the end-use stations. Logistics work involves the terms of harvesting, collecting, baling, and handling
11 process [71]. The logistics system interconnects between the sources of feedstocks and the bioenergy industry, directly
12 connected to the size of production units, plant location, transportation system [72, 73]. Other than the feedstocks to energy
13 conversion that influences the production cost, logistics management can enable the optimization of the plants scale, implying
14 the location based on the optimal distance of the supply site, which can enhance the cost minimization [74, 75].

15 16 Economic feasibility

17 Three indicators applied in the evaluation in this study comprise ‘Net present value (NPV)’, ‘Final price per liter’, and
18 ‘Added value of input materials’. In terms of business feasibility, NPV indicates the profitability from future cash flows during
19 the investment lifetime after discounted to the present value, which is a parameter to analyze the attractiveness of a project
20 investment [76, 77]. An estimated price of ethanol, including all costs in the supply chain, is also imperative to determine the
21 project’s feasibility. NPV can be calculated from the expenses generated from all elements in the production chain, such as the
22 capital cost from equipment installation, and the operational cost from biomass management and production [76].

23 The final selling price could be referred as the structure of minimum ethanol selling price. Principally, the final price of
24 biofuel is constructed from costs of raw material and production process under the condition of 10% internal rate of return
25 (IRR). The production cost of bioethanol from lignocellulosic feedstocks comprises the capital costs of the production plants
26 and the operational cost. In spite of the cost of cellulosic raw materials that is lower than from the conventional sugar- or starch-
27 based biomass [78, 79], the competitiveness in terms of economic viability, comparing to the first-generation, it has always
28 been inferior for the second-generation bioethanol, especially due to the cost of conversion process, including cellulase enzyme
29 and microbes for fermentation [30, 80]. Nonetheless, for the bioethanol retail price in Thailand, there are several elements
30 which stimulate the growth of bioethanol in the market, for instance tax exemption or subsidization [38]. Currently, in Thailand,
31 the price of ethanol has not been regulated by the government but rather determined by the actual ethanol trading price between
32 ethanol manufacturers and oil traders [81].

1 In addition to the economic analysis from the production process, the possibility to extend the added values of input
2 materials is also a vital factor to consider. Conversion of biofuel from the residues has high potential in the value addition,
3 varying on the types of input materials and the output products. The value addition of the biomass from conventional production
4 can increase through the technological development [82, 83]. Compared with the biofuel productions from crop farming,
5 utilizing lignocellulosic biomass as input materials for higher value-added was assessed to give more economic benefits and
6 socio-economic advantages such as expanding the employment rates [84]. In recent years, industrialized ethanol production
7 from lignocellulosic biomass has transformed from only ethanol production to value-added co-products. For example, from
8 fermentation process of the residual by-products, it is possible to derive lignin plastic composite material simultaneously as
9 biorefinery productions [85].

11 Social impacts

12 The social benefits and drawbacks for the locals should be concerned when the project of production plants is
13 implemented, referring to influential indicators for policy implications [86]. The criteria under this topic are selected based on
14 social impacts, including ‘Job creation’, ‘Food security’, and ‘Change in household income’. As it has been investigated by
15 Brinkman et al., macroeconomic impacts such as income and employment rates are often used in the field of bioenergy [87].

16 Job creation can relate to several spectra of indications, such as an employment rate, income generated, and the ratio of
17 skilled/unskilled laborers [87]. Commonly, job creation is the key indicator being used in the socio-economic assessment [31,
18 59, 88], which is undertaken as a bottom-up analysis method by demonstrating from the production process [87]. The model
19 of decentralized production plants is especially an attractive scenario to create higher employment rates as beneficial for
20 regional development [59]. Factors regarding job creation and added values are also important for evaluating the bioeconomy
21 since the enhancement of the bioeconomy potentially increase the value-added per person due to the improvement of labor
22 productivity [84].

23 In the case that the production of food crops is associated with non-food purpose business, it is necessary to take the
24 factor of food security into account. The increase of biofuel demand has led to the rising price of maize, which affected the
25 contribution of grains production in the food industry became smaller due to the expansion of land use [89]. The parameters
26 related to food security imply the sufficiency of food for the inhabitants regarding physical, social, and economic possibilities.
27 The indicators are associated with, for example, the sufficiency of food availability, changes in areas of food crops, food
28 accessibility, reasonable price, and sufficient calorie intake [89, 90]. Nonetheless, utilizing agricultural residues is prospected
29 to lessen the conflicts on food price competition from land use with conventional counterparts [91].

30 Another engaging variable in the study of the socio-economic aspect is the indicator of household income. This indicator
31 is used in monitoring economic growth as part of sustainable bioeconomy development [15]. Household income can be used
32 to indicate equality by evaluating the income distribution subjected to the rural and urban areas as a diversity of income exists,

1 particularly in the developing countries [92]. In conventional bioenergy, the agriculture-oriented households are influenced to
2 shift to producing energy crops by the biofuel policy and prospective household income [93]. On the contrary, for the advanced
3 bioenergy projects, the expectable incomes rely significantly on the required jobs in the facility construction, plant operation,
4 and the capacity of the plant [94]. Moreover, the process of collecting agricultural residues would be a favorable incentive for
5 the local crop producers, as it might provide additional income in addition to crop cultivation [95].

6 Environmental impacts

8 Biofuel promotion is an effective tool for the substitution of fossil fuel. However, an extensive production and
9 consumption have induced several adverse effects, including expanding land use and GHG emission [44, 96]. With a goal to
10 optimize the bioenergy to achieve sustainability in development, environmental indicators are compiled to be prioritized in the
11 study. Three parameters, namely 'Indirect land use change (iLUC)', 'Net energy balance' and 'Greenhouse gas (GHG) balance',
12 are selected for the survey interview.

13 The iLUC indicator has been widely applied in the evaluation of biofuels since it is an indicator that directly indicates
14 the consequence of alternating previous activity in the cropland into bioenergy targeted production. This indicator has been
15 remarked as more complicated than direct land use due to its definition since the evaluating method includes the outside areas
16 of the monitored biomass production [97]. In the case of the cultivation land in Thailand, the land use for bioenergy production
17 mainly expands from the displacement of other existing crop cultivation. Risks of iLUC have been investigated from the current
18 bioethanol production from cassava and sugarcane comparing to fossil fuel. The study revealed that GHG emissions per liter
19 from conventional feedstocks occupied around 40-80% of that from fossil fuel after including the iLUC [98].

20 In terms of energy analysis, net energy balance is a parameter for assessing environmental impacts, indicating how the
21 efficiency of the bioenergy production process is. Accordingly, it can be applied with a life cycle assessment to evaluate CO₂
22 balance [99]. This indicator defines a comparison between required input energy and achievable ethanol to measure the positive
23 or negative outcome, considering the process of converting raw materials into ethanol, which varies heavily on the type of
24 primary energy consumption. Along with the flow of energy input-output, the process involves not only directly with CO₂
25 emission but also with cost factors, which can determine the feasibility of the project [100].

26 Net energy yield has also been analyzed in terms of gross energy yield per area as evaluated by Vries et al. The
27 assessment helps select adequate bioenergy production resources, which gives the highest net energy yield [101]. However, the
28 value is not limited to energy per area, but it also involves required energy factors during the production process, such as farm
29 machinery, fertilizing system and product transportation [100, 101]. Referring to the investigation by Mishra et al., bioethanol
30 production from wheat straw resulted in net energy ratio (NER) >1. Nonetheless, the study remarked that the NER would be
31 offset depending on the types of consuming energy in the process.

1 The GHG balance refers to the GHG reduction comparing to the emission throughout the production phases, which
 2 relies on various factors, such as types of fossil fuel and fertilizers in crops plantation [102]. GHG balance has been attracted
 3 to researchers in the study of conventional bioenergy since it showed the negative balance (input > output) from energy crops
 4 cultivation and the soil carbon sequestration [103]. In addition to the GHG emission from land use change, the life cycle CO₂
 5 from farm to end-products is the factor to compare CO₂ mitigation with the conventional biofuel production and fossil fuel
 6 [104], since types of fuel as an input energy influence the total GHG balance. Meanwhile, it is possible to save output GHGs
 7 with the generated co-products in the biofuel production system [105].

8

9 Table 1 Sets of indicators for the purpose of bioenergy evaluating application

Main criteria (Aspects)	Sub-Criteria	Units	References
Technical feasibility	Biomass availability and collectability	Kg ha ⁻¹ y ⁻¹	[68, 69, 106]
	Ethanol productivity	Liters kg ⁻¹	[107, 108]
	Biomass logistics	Ton day ⁻¹ , km ² day ⁻¹	[73– 75]
Economic feasibility	Net present value	US\$	[76, 109, 100]
	Final price per liter	US\$ Liter ⁻¹	[110, 111]
	Added value of input materials	US\$ ton ⁻¹ y ⁻¹	[82, 112, 113]
Social impacts	Job creation	Persons y ⁻¹	[31, 86, 114]
	Food security	US\$ tons crops ⁻¹ , Tons ha ⁻¹ or Kcal capita ⁻¹	[90, 115, 116]
	Change in household income	US\$ y ⁻¹ or US\$ household ⁻¹ y ⁻¹	[92, 103, 117]
Environmental impacts	Indirect land use change	(Biomass growing capacity) ha ⁻¹ y ⁻¹ or kg CO ₂ -eq (Biomass growing capacity) ⁻¹	[98, 118]
	Net energy balance	GJ ha ⁻¹ y ⁻¹	[101, 119, 120]
	GHG balance	Tons CO ₂ equiv. year	[102, 104, 121]

10

11 Analysis of the survey data from AHP method

12 After retrieving quantitative and qualitative opinions from the participatory Delphi survey conduction in this study, AHP is
 13 applied to interpret the subjective opinions and systematically transform them into objective information. AHP is a tool that
 14 helps make decisions from complex sets of alternatives to reach the goal of multi-attributes decision-making [122]. The

1 complexity from a variety of quantitative data is able to be reduced and become one-dimensional figures. According to Saaty,
 2 the AHP method is mainly performed by two steps comprising the hierarchical structure and rating the scales on elements in
 3 pairwise comparisons [58].

4 The criteria were reviewed via pairwise comparisons using the provided rating scores, as the intensity of importance and
 5 definition are shown in Table 2. Since the format of criteria weighting was designed for the participants to rate by selecting a
 6 level of intensity from multiple choices (**Supplementary information**), in order to process the data according to AHP, it is
 7 necessary to convert the reviewed criteria and intensities into the matrix form. If the respondents vote for the left column
 8 criteria, the scales of 1-9 shall be filled out in the matrix for specifying that the row was more important than criteria from the
 9 column. In the reverse case, if the variables were located towards the right side, then criteria on the row were intended to be
 10 less important. Thus, the reciprocal numbers; 1/3, 1/5, 1/7, 1/9, or 1/2, 1/4, 1/6, 1/8 have to be placed for restructuring.

11
 12 Table 2 Scales of importance for using in pairwise comparison

Intensity of importance on an absolute scale	Definition	Explanation
1	Equal importance	Two activities contribute equally to objective
3	Moderate importance of one over another	Experience and judgment favor activity over another
5	Essential or strong importance	Experience and judgment strongly favor one activity over another
7	Very strong importance	An activity is strongly favored and its dominance demonstrated practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values between the two adjacent judgments	The scores using when compromise is needed

13
 14 The matrix A is structured from $n \times n$ criteria as presented in the equation 1.

15
$$A = \begin{bmatrix} 1 & a_{12} & \dots & a_{1n} \\ a_{21} & 1 & \dots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \dots & 1 \end{bmatrix} \quad \text{Eq.1}$$

16 Then, matrix A is converted into normalized matrix in order to calculate the relative weights from the same level of criteria
 17 that reflect the preference scores as input by the experts. The matrix \bar{A} is a normalized pairwise matrix of matrix A, resulting
 18 from dividing each value in the same column by summation of factors in the respective column. The step of normalization is
 19 the calculation for the results of relative weights, where all the elements are a sum of 1. The derived values of each element

1 from the same column indicate the relative weights of the criteria constituted in the matrix. The steps of calculating normalized
 2 matrix can be referred from the study by Kheybari et al [123].

3 In addition to the calculation of relative weights, the calculated results ought to be examined for consistency to verify the
 4 reliability of the data. The following steps are described to verify the AHP consistency.

$$5 \quad \bar{A} \cdot \bar{W} = \lambda_{max} \cdot \bar{W} \quad \text{Eq. 2}$$

6 Where \bar{W} refers to the weighted sum vector as quantified from eigenvector calculation. Meanwhile, λ_{max} is the maximum
 7 eigenvalue, which can be obtained from average values in vector \bar{W} of matrix A.

$$8 \quad C.I. = \frac{(\lambda_{max} - n)}{(n-1)} \quad \text{Eq. 3}$$

$$9 \quad C.R. = \frac{C.I.}{R.I.} \quad \text{Eq. 4}$$

10 When n indicates the size of the matrix, in this study, n = 4 and 3 for the main criteria and sub-criteria, respectively.
 11 Consistency index (C.I.) and consistency ratio (C.R.) can be determined, as shown in Eq. 3 and 4, respectively. This value can
 12 be calculated from the random index (R.I.), as clarified in Table 3, identified by Saaty vary on the matrix size (N). An acceptable
 13 C.R. for rational decision-making suggested being lower than or equal to 0.1 [58]. Even though the consistency can identify
 14 the trustworthy, due to human based judgement, it is highly possible for the data to fall into inconsistency. Especially, the larger
 15 size of numbers of criteria can possibly result in inconsistency. In spite of the mentioned CR, in some cases, such as in a group
 16 evaluation, the C.R. between 0.1-0.2 is also acceptable [124]. Otherwise, the exceeding C.R. suggested to re-implement the
 17 criteria comparison.

18
 19 Table 3 Scales of random index as experimented by Saaty [58].

Matrix size (N)	1	2	3	4	4	6	7	8	9	10
Random Index (R.I.)	0.00	0.00	0.58	0.9	1.12	1.24	1.32	1.41	1.46	1.49

20
 21 Due to the allocated numbers of panelists in each group that was not equal in all sectors, the individual responses were taken
 22 for arithmetic average. This step was conducted within each organization group before calculating the overall mean values for
 23 all participants, as previously shown in the studies of experts participatory evaluation [123, 125].

24 Apart from the set of criteria as indicated in the pairwise comparison matrix, this study provided more opportunities for
 25 experts to select additional concerning points and suggest supplementary criteria, which are considered important in the
 26 respective context.

1 Results

2 Experts panel

3 The experts participated from 5 different fields; governmental sectors, industrial sectors, non-profit/non-governmental
4 organization, academic/research institutes, and financial organizations. For the survey conduction in the first round, total 20
5 respondents from 29 contacted targets consented to attend in the survey participation. The selected experts' fields covered all
6 range of associated players in the bioethanol production chain in Thailand within the boundary of origin of resources to
7 bioethanol production. However, as the governmental section works closely as a facilitator and regulator of the private sectors,
8 they are more familiar to the vital policy making, reflecting to the major proportion of governmental experts structured in the
9 experts panel.

10 Due to only few feedbacks were returned in the second round in this performed survey, the survey interval stopped until
11 round two. As a process of round two, after informing the round one results, the surveys were sent to the participants, while 4
12 respondents (20%) returned their responses, and only 2 participants made a modification of the answers from the first round.
13 Regarding the marginal number of feedback in the second round, we terminated the further rounds of the survey. The numbers
14 of round have been reported to be varied but found average at two to three rounds [126]. Many studies stopped at the second-
15 round [122, 127]. The ratio of respondents who responded to re-evaluate in the second round in this study is considered to be
16 comparable ratio to previous Delphi-AHP research [128].

17 During the time of survey conduction, engagement with the organizations was the most challenging part. The regular
18 organizational system limited the access to connect with the experts directly, but it needed to be delegated from the executive
19 levels to responsible for survey answering. In this way, there was the circumstance that the persons neglected to reply since
20 they did not feel their prominent role as a decision-maker to the topic. Nonetheless, according to the institutional system, the
21 delegation could guarantee that the participants are well qualified to responsible for the task. Meanwhile, regarding the
22 limitation, we managed the lack of engagement by constantly revising the approach, such as attempts to communicating more
23 frequently, providing insightful information, and searching for alternative ways of personal connection. In some cases,
24 especially from the private firms, the decision to attend the survey were taken based on their core business of the institutes.
25 This means that the enterprise's background is one of the explainable reasons for not being able to commit to every contacted
26 respondent.

27 The result from round one and round two did not significantly differentiate results since only small numbers of the returning
28 responses in round two. The participated organizations with numbers of the respondent are summarized in Table 4. As
29 categorized by branches of expertise, proportions of participants are shown in Figure 3, elaborating that the structure of expert
30 panels comprises of 6 experts from governmental sectors, 5 experts from private sectors, and 3 experts from each Non-Profit
31 Organization NPO/NGO, academic and financial institute.

32

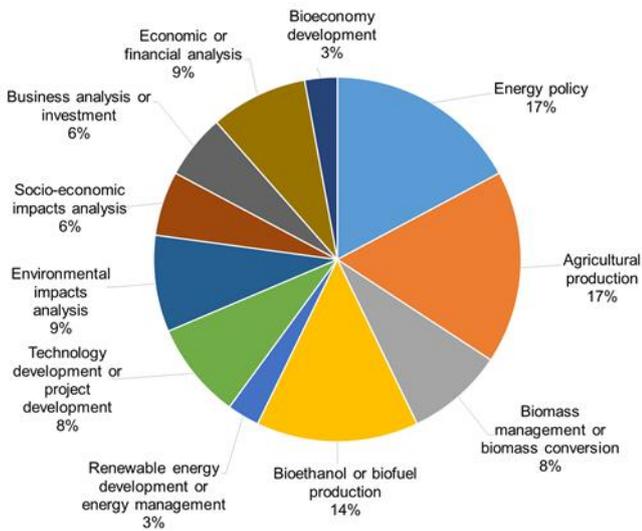
1 Table 4 Number of respondents by types of organization

Type of Organization	Contacted numbers	Number of respondents (round one)	Number of respondents (round two)	Proportions [%]
Government / Ministry / Policymakers	8	6	-	30
Industry / Business sectors	10	5	-	25
Non Profit Organization (NPO) / Non Governmental Organization (NGO)	3	3	1	15
Academic / Research Institute	4	3	2	15
Financial institution / Bank	4	3	1	15
Total	29	20	4	100

2

3 Backgrounds of expertise were undertaken in order to breakdown the reasons for supporting the results, which was expected
 4 to assist in the interpretation of the AHP with the empirical factors of different backgrounds. Figure 3 illustrated the proportions
 5 of panelists from diverse branches of familiarity with the topics and professional categories. It is notable that the participants
 6 are majorly accustomed to the topics of energy policy and agricultural production. The second most allocated background was
 7 in bioethanol or biofuel production.

8



9

10 Figure 3 Proportions of areas of expertise in a group of participants

11

1 Results of AHP analysis

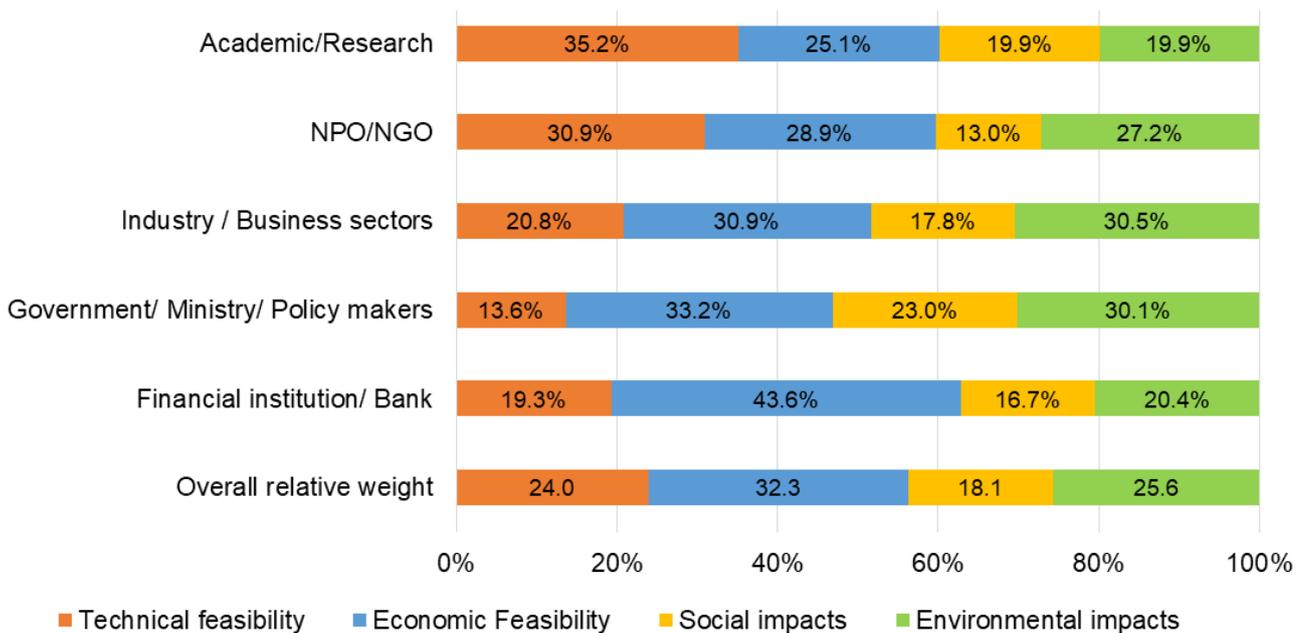
2 Prioritization of main criteria

3 Results of the relative weights of the main criteria from round one to round two showed slight changes. However, the
4 ranking of preferable main criteria remained the same. The result of relative weights from the second round is shown in Figure
5 4. Based on the scores of pairwise comparison from every respondent, the Consistency Index (C.I.) was ranging from 0.000 –
6 0.074, whereas the calculation of Consistency Ratio (C.R.) resulted in between 0.000 – 0.083. According to Saaty, if the C.R.
7 is <0.1, the answers of evaluation by all participants were verified to be consistent. Among the four main criteria as the overall
8 weight presented in Figure 4, ‘Economic feasibility’ gained the highest priority (32.3%). Following that, the second and third
9 ranks were resulted in ‘Environmental impacts’ (25.6%) and ‘Technical feasibility’ (24.0%), respectively. Lastly, the criteria
10 weights for ‘Social impacts’ resulted in the least important (18.1%).

11 When considering the scores of preferable criteria by categorizing based on expert panels, it is noticeable that the results
12 could be divided into two groups. First, the group of governmental organizations, industry/business sectors, and financial
13 institutes, where the ‘Economic feasibility’ showed noteworthy high scores. The other was the expert groups that prioritized
14 ‘Technical feasibility’ as the most preferable, as found in NPO/NGO and academic or research institutes.

15 Comparing ‘Environmental impacts’ and ‘Social impacts’, except for the group academic/ research institute, most of
16 the experts rated the ‘Environmental impact’ as more important than the latter. Interestingly, NPO/NGO showed more attention
17 to the technical aspects, as it can be seen the merely higher scores than those from economic and environmental criteria. On
18 the other hand, the industry and business sectors gave higher prioritization for economic and environmental aspects, comparing
19 to technical and social dimensions.

20



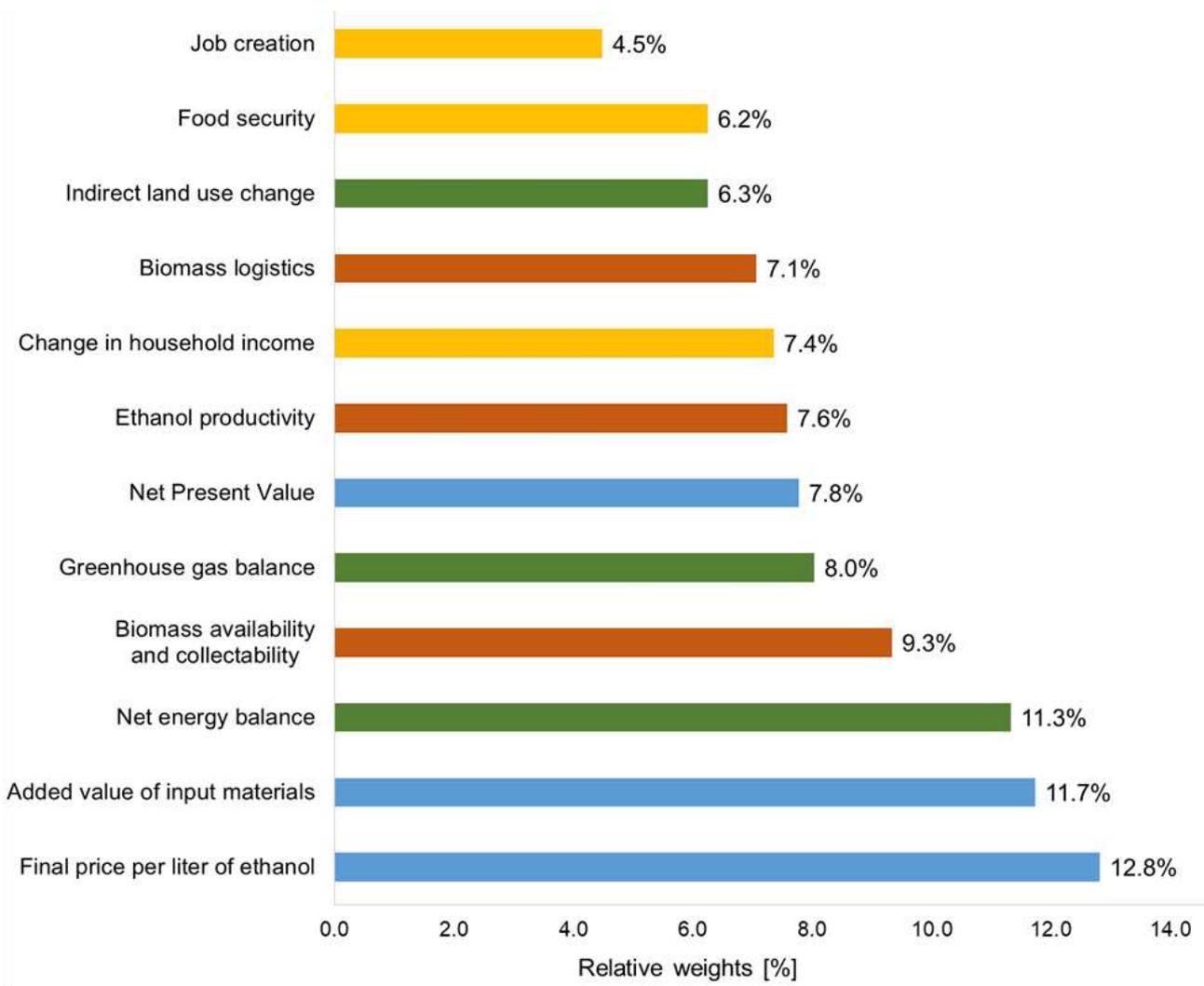
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22 Figure 4 Main criteria prioritization divided by types of organizations and overall scores from all participants

1 **Prioritization of sub-criteria**

2 The second level of criteria was assessed as sub-criteria, which interconnected to the four main subjects, as mentioned
3 in 3.2.1. From the criteria evaluation of the first round and adjustment from the second round, the average values of sub-criteria
4 weighting were obtained from 20 respondents. As a result of the consistency analysis, the average values of C.I. were calculated
5 from sub-criteria in four main-criteria; technical, economic, social and environmental aspects, resulted in 0.011, 0.017, 0.008,
6 and 0.007, respectively. Meanwhile, the average values of C.R. were computed to be 0.019, 0.030, 0.014, and 0.014 from the
7 same respects. The results of C.R. from all participants in the evaluation of the sub-criteria have proved the consistent level in
8 the study.

9 The results of normalized evaluations of overall sub-criteria are shown in Figure 5. The top three priorities were occupied
10 by the sub-criteria from ‘Economic feasibility’ and ‘Environmental impacts’. The highest priority was voted from ‘Final price
11 per liter of ethanol’ (12.8%), following by ‘Added value of input materials’ (11.7%) and ‘Net energy balance’ (11.3%). On the
12 other hand, the sub-criteria ‘Food security’ (6.2%) and ‘Job creation’ (4.5%) from ‘Social impacts’ were prioritized at the
13 lowest two criteria.



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15 Figure 5 Range of relative weights in each sub-criteria

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Table 5 presented the relative weights in respective main-criteria and overall relative weights of sub-criteria. The minimum and maximum weights were clarified with the values of standard deviations in order to indicate the range of voted scores by experts. From the comparison of criteria in the aspect of ‘Technical feasibility’, the ‘Biomass availability and collectability’ showed the highest weighting scores (38.9%). This result could be related to the fact that second-generation bioethanol heavily depends on the quantity of agricultural residues considered to have a scattered availability. The result was identical to the weight for technical factors evaluated in the study of Kheybari et al [123]. Kheybari described reasons to support the importance of biomass availability that the factor of availability is associated with the logistic feasibility from biomass sources to the demand side.

In the dimension of economic feasibility, the experts prioritized ‘Final price per liter of ethanol’ as the most important criteria (39.6%). This outcome identified the concern regarding the production cost of biofuel prices from agricultural residues. The concern was considered to be logical from the current status due to the fact that it is an under-commercialized technology in Thailand, implying the lack of referenced market prices.

Next, ‘Change in household income’ was the most dominant criterion from the social impacts. According to the study of von Doderer et al., employment income regarding a factor in socio-economic aspect could be determined based on the selling of products, or from selling power generation [117]. Payment to households could be an intriguing reason for the local people to accept a novel technology for the reason that the project can be related to the thriving economy in that local area [129].

Lastly, ‘Net energy balance’ occupied the largest proportion of the main-criteria ‘environmental impacts’. This factor indicates the efficiency and effectiveness of energy conversion from the biomass, influencing carbon emissions [130]. The process of biofuel production affects the ratio of input and output of energy. With the energy indicator, it is possible to justify the sustainability level between renewable biofuel and the conventional fuel [131].

Table 5 Summary of relative weights of main-criteria and sub-criteria weights as analyzed in this study

Main-criteria	Relative weights	Sub-criteria	Relative weights	Overall Relative weight	Min. weights	Max. weights	Standard deviation (SD)
Technical feasibility	24.0%	Biomass availability and collectability	38.9%	9.3%	1.8%	17.4%	5.38%
		Ethanol productivity	31.6%	7.6%	1.6%	16.6%	5.62%
		Biomass logistics	29.5%	7.1%	1.7%	17.9%	6.07%
		sub total	100.0%				
Economic feasibility	32.3%	Net Present Value	24.1%	7.8%	2.2%	22.4%	6.87%

		Final price per liter of					
		ethanol	39.6%	12.8%	2.9%	25.1%	6.97%
		Added value of input					
		materials	36.3%	11.7%	2.2%	26.4%	8.39%
		sub total	100.0%				
Social impacts	18.1%	Job creation	24.8%	4.5%	1.3%	12.4%	3.47%
		Food security	34.5%	6.2%	1.2%	13.1%	4.03%
		Change in household					
		income	40.7%	7.4%	3.4%	13.2%	3.66%
		sub total	100.0%				
Environmental impacts	25.6%	Indirect land use			1.9%	16.2%	5.12%
		change	24.4%	6.3%			
		Greenhouse gas			2.7%	17.7%	5.19%
		balance	31.4%	8.0%			
		Net energy balance	44.2%	11.3%	1.8%	18.3%	5.86%
		sub total	100.0%				
Total	100.0%			100.0%			

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Besides the overall criteria prioritization, the sub-criteria weights were categorized separately into types of organizations and branches of backgrounds (see Figure 6). In Figure 6, the relative weights of 12 sub-criteria were classified in the 5 groups of experts. Meanwhile, Figure 7 presented the Sankey diagram showing the relation between different backgrounds with organizations of participants, connecting to diverse results of criteria priority.

3

4

The highest priority of criteria from the experts in the Financial institutes/Bank was significantly occupied by ‘Final price per liter of ethanol’ (22.5%). This result reflected the viewpoint that the biofuel prices must be considered in the project initiation of second-generation bioethanol. In general, banks consider the project potential from NPV and IRR, which will result in the decision in financial loan to the investors for newly constructed projects or factories [132].

5

6

Following that, for the academic and research institutes, the factor ‘Biomass availability and collectability’ was voted for the highest priority (13.3%). Surprisingly, even though the representatives from academic institutes were allocated from the background of the environment, the concerns on environment related topics were relatively lower than expected. Similarly, the results of the highest priority evaluated by the NPO and NGO also emphasized the importance of ‘Biomass availability and collectability’ from the technical aspect (19.6%). Regarding the results from the industry and business sector participants, although the proportions of main criteria were dominated by ‘Economic feasibility’, the largest percent of sub-criteria was ‘Net energy balance’ (15%) from the category of environmental impacts.

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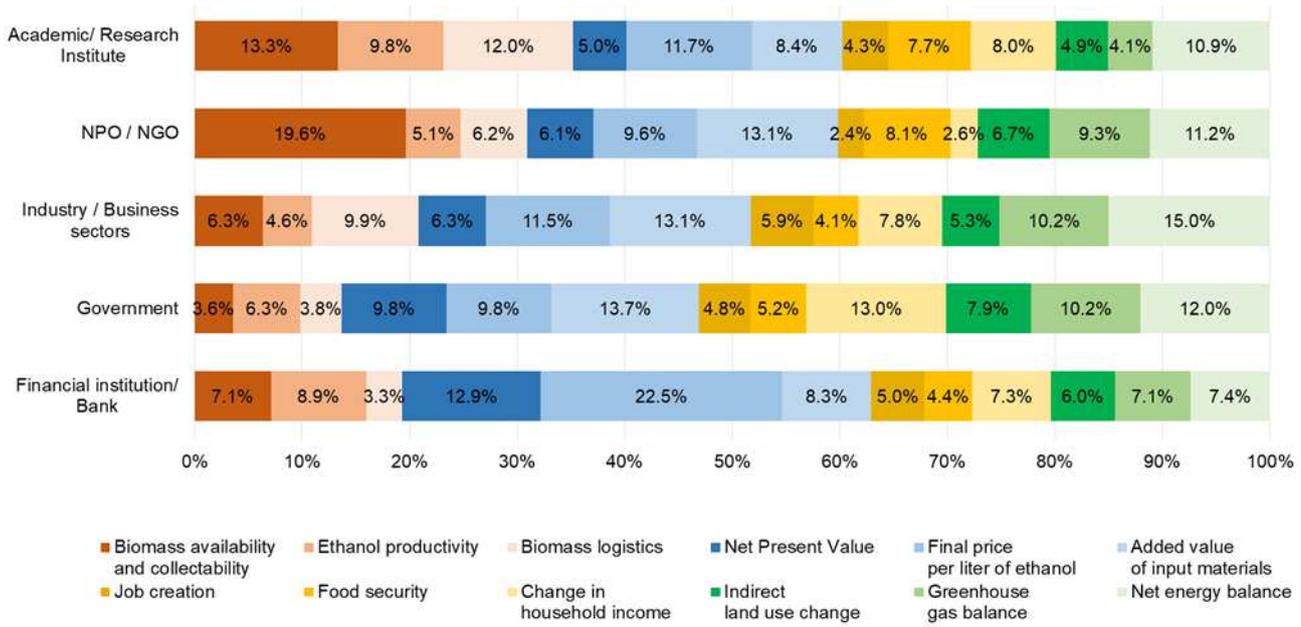
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1 Unlike the other organizations, the governmental sector showed similar proportions in each criterion in terms of relative
 2 weights allocation. There was no significantly high proportion among 12 attributes; however, the highest score was the ‘Final
 3 price per liter of ethanol’ (13.7%). The retail price of biofuel affects governmental subsidization since Thailand uses the
 4 mechanism to maintain the price gap between biofuel type and fossil fuel to promote consumption of renewable energy [133].
 5 Therefore, this criterion resulted in being attractive for policy-makers to consider cost-benefits at the national level.
 6



7
 8 Figure 6 Relative weights for each sub-criteria as categorized by stakeholders in this study
 9

10 **Connection between the expertise backgrounds, organizations and prioritized criteria**

11 For more understanding of the results regarding the expert judgement, the participants’ backgrounds were collected as
 12 inquired in the questionnaire form. Figure 7 showed the connection between the experts’ backgrounds, their affiliations,
 13 together with the outcomes of prioritization, constructing in the Sankey diagram. As a result of illustration, it was not possible
 14 for one participant from an organization to hold expertise in every subject. Nonetheless, all survey respondents could cover all
 15 necessary fields to fulfill the elements of value chain in this study. According to the survey results, the most associated fields
 16 of experts are in ‘Energy policy’ (17%) and ‘Agricultural production’ (17%), following by ‘Bioethanol or biofuel production’
 17 (14%). On the other hand, the least familiar topics for all participants were ‘Renewable energy/energy management’ (3%) and
 18 ‘Bioeconomy development’ (3%).

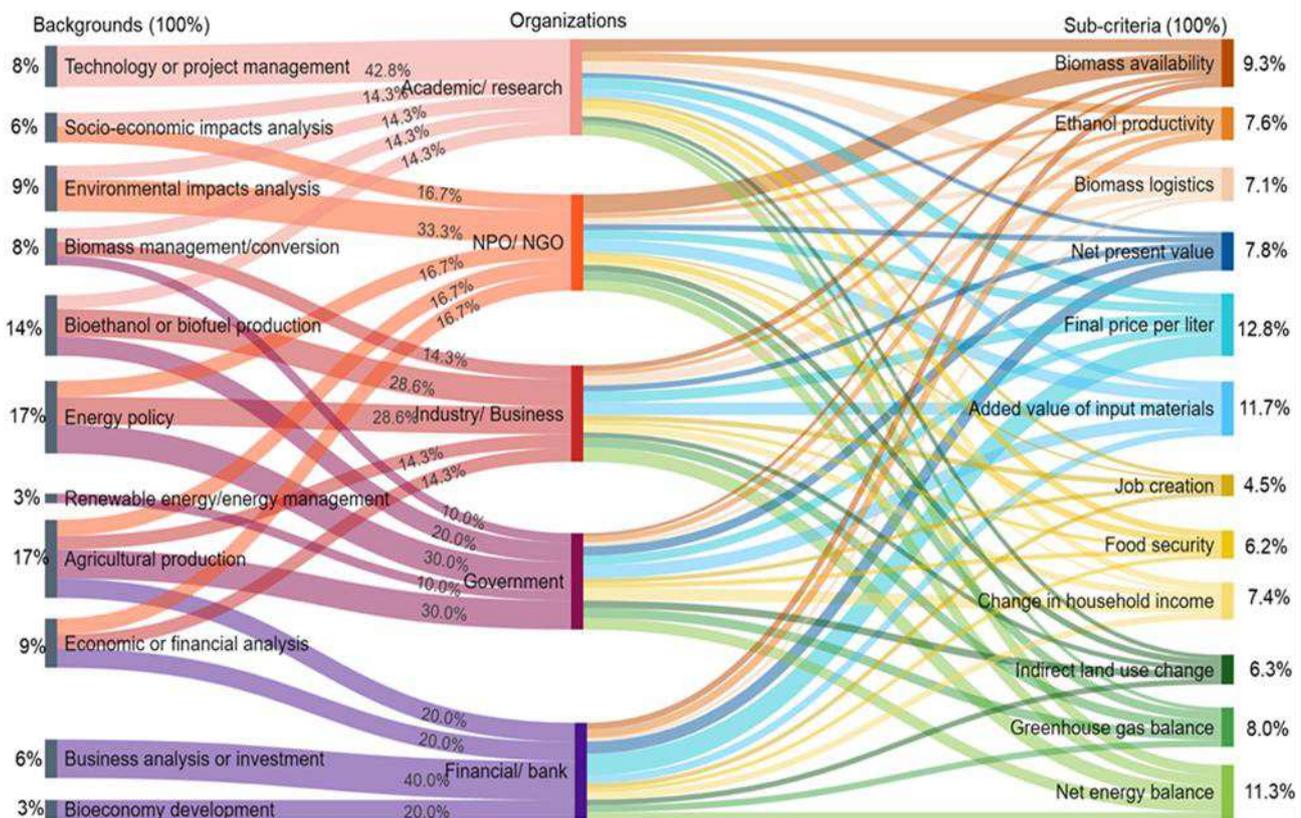
19 Interestingly, despite the results that the respondents from the governmental and academic sectors did not hold the
 20 expertise in the financial or business analysis, the most weighted criteria were reflected to ‘Final price per liter’. Considering
 21 this preference, it is assumable that the participants might view the criteria ‘Final price per liter’ from different angles of pain

1 points or requirements. For instance, this parameter could be interpreted as the profitable rate for the ethanol manufacturers,
 2 whereas the ethanol price can indicate the necessary incentive to persuade consumers from the governmental perspectives.

3 Looking at the connection between the highest voted criteria under each organization (Figure 6) and the relationship
 4 with their backgrounds (Figure 7), most of the participants from Academic/research hold the background of ‘Technology and
 5 project management’ – voted for ‘biomass availability and collectability’ to be the most important. A similar result can be seen
 6 from NPO/NGO, with the majority of backgrounds in ‘Environmental impacts analysis’ gave the highest priority to the same
 7 criteria. The NPO/NGO were the organizations that engaged significantly with broad topics, including environmental,
 8 bioethanol, energy policy, agriculture, and socio-economic aspects. The output from the NPO/NGO is motivating to involve
 9 their perceptions in the early stage of policy-making process in order to avoid a possible disagreement towards public policy
 10 implementation.

11 Meanwhile, the experts from Industry and business sectors are associated mostly with ‘Bioethanol and biofuel
 12 production’ as well as ‘Energy policy’. Their prioritized criteria went to ‘Net energy balance’ from the environmental aspect.
 13 Following that, the most voted variable from the experts in the governmental sectors was ‘Added value of input materials’,
 14 although it can be seen that the related backgrounds were mainly located in ‘Energy policy’ and ‘Agricultural production’,
 15 which are not directly connected to the economic aspect. In comparison to the results from other organizations, the stakeholders
 16 from Financial/bank emphasized the importance of ‘Final price per liter of ethanol’, which was also resulted in the most
 17 evaluated criteria from overall participants.

18



19

1 Figure 7 Sankey diagram for illustrating the relationship between the categories “Field of expertise”, “Type of organization” and “Criteria
2 weights” as derived from the Delphi-AHP results

3

4 Additional criteria and supplementary comments

5 Besides the pairwise comparison from the provided criteria, the participants were asked to select the relevant criteria
6 from multiple lists of topics. The aim of compiling additional criteria is to explore other possible elements from the sentiments
7 of stakeholders. The additional criteria are expected to contribute to designing the implications of scenarios in the further steps
8 studies.

9 The summary of further remarks is summarized in Table 6. It is remarkable that the most frequently selected criterion
10 by all participants was ‘Dependence on subsidy’. The most attention receiving factor emphasized the perceptions towards the
11 role of government in the policy recommendation. Unsurprisingly, the technology readiness level resulted in the second most
12 votes. Regarding the current status that the second generation bioethanol progressed at the pilot scale-production, the result
13 suggested that it might still be too early for projection from their perceptions.

14 The second and third most voted additional criteria were derived from technological feasibility, namely ‘Technology
15 readiness level’ and ‘Co-products’. On the other hand, it is noticeable that the environment related criteria gained rather limited
16 priority, such as output wastes, forest areas, and fertilizers/ pesticides. In addition, the social aspect criterion, ‘Job quality’, was
17 voted by only one score. The results of additional criteria in this part have demonstrated overlapping results to the sub-criteria
18 evaluation.

19

20 Table 6 Frequency of mentioned topics as additional criteria

Mentioned topics	Government	Industry /			Academic/	Financial	Total
		Business	NPO / NGO	sectors	Research	institution/ Bank	
Governmental subsidy	3	2	2	1	3	11	
Technology readiness level	2	2	1	2	2	9	
Co-products	3	1	1	2	1	8	
Air pollution level	1	-	2	3	1	7	
Water management and irrigation system	1	1	1	-	2	5	
Material balance	-	1	-	2	1	4	
Output wastes	1	1	1	-	1	4	
Forest areas	1	-	1	-	1	3	
Fertilizer and pesticides	-	1	1	-	-	2	

Job quality	-	-	-	-	1	1
Land prices	-	-	-	-	-	0

1

2 Supplementary comments were compiled from the participants' opinions simultaneously in the surveying process. The
3 comments were summarized and elaborated by groups of experts in Table 7. It is noticeable that the raised-up viewpoints
4 reflected the insights based on their experiences. Some comments hinted at the underlying issues that should be properly
5 discussed across multi-sectors. As it can be noticed from the comments, the governmental role is crucial for endorsing the
6 strategic development of bioenergy. This involves governance-related elements, including laws and regulations that can support
7 the upcoming advanced technology and, more importantly, the incentivized system structure. Meanwhile, the participants also
8 emphasized the importance of competitiveness in the biofuel market from economic perspectives, which needs to be approached
9 for biofuel producers and market expansion for bioenergy. Moreover, several have mentioned factors, which have not been
10 provided in the current study, such as risk management and ethanol quality. Nonetheless, due to the concerns regarding under
11 commercialized status, the technical feasibility would need to be verified as a transformation threshold. These retrieved
12 comments were deemed to be valuable for creating future scenarios and evaluating for further study.

13 Table 7 Supplementary remarks from the participants categorized in branch of experts

Group of experts	Supplementary comments
Government	<p>“Appropriate fuel price structure needs to be clarified.”</p> <p>“Incentive by the government to promote project initiation.”</p> <p>“Ethanol quality to be blended with the gasoline needs to be controlled for the reliability.”</p>
Industry / Business sectors	<p>“The role of governmental policy is critical to take part in.”</p> <p>“Mechanism analysis to drive the expansion of the biofuel market.”</p> <p>“Products from the agricultural residues should not limit to only biofuel production, but the technology for value-added products should be integrated into the value chain.”</p>
NPO / NGO	<p>“Other indicators for the analysis of environmental impacts can be specified by several indicators, such as conversion of GHG emissions per farming area, total GHGs from all production cycle by comparing the scenarios of fossil fuel and biofuels, and impact assessment on biodiversity.”</p> <p>“Wastewater treatment should be concerned in the process.”</p>
Academic/ Research Institute	<p>“There is a possibility that the weights of the criteria will change over time. The weights I provided are the opinions based on the assumption that the 2nd generation bioethanol is not a market-ready technology.”</p>

“Even though the viability in the financial terms could be confirmed, technological feasibility is the imperative issue that has to be achieved.”

“The comprehensive study on risk management for commercialization of the second-generation bioethanol technology.”

Financial institution/ Bank

“The criteria evaluation in the study is mainly focused on the supply side; however, the criteria evaluation from the demand side, which can influence ethanol consumption, should also be taken into consideration.”

“It is still questionable regarding the possibility for the advanced bioethanol to complying with the current law and regulations.”

“Is the level of competitiveness between the bioethanol producing corporates high enough?”

1

2 Discussion

3 With the tool of Delphi-AHP, as demonstrated in the current research, it has been verified that the qualitative perceptions
4 from 20 stakeholders could be transformed into quantifiable criteria. Diverse opinions depicting scattered attitudes towards the
5 topic could become reconciled. Moreover, the participatory evaluation, as practiced in this study through Delphi-AHP, has
6 emphasized the stakeholders to recognize the importance of their roles in the policy launching process, which encourages
7 transparency and engagement to the creation of sustainable policy. The additional criteria and supplementary comments raised
8 from the participants have identified the experts’ understandings and concerns in regards to the topics.

9 Regarding the most attentive aspect that was voted for economic feasibility, the reflection from the respondents to economic
10 viability could be contemplated from the supply and demand side. The supply side was likely inferred to the concerns towards
11 investment cost and financial attractiveness due to new emerging technology. A similar result was also remarked in the literature
12 studies that the investment cost is the most critical criterion for the economic aspect [111]. For the demand side, fuel price
13 instability could be a matter of concern for consumers. Belonging to the economic aspect, the biofuel price was the most focused
14 factor from overall relative weights.

15 When considering the cost structure of bioethanol, the raw material price can influence 40 - 60% of the minimum selling
16 price [134]. Thus, the changing of biomass prices may majorly cause the fluctuation of biofuel selling prices. In addition, the
17 declining crude oil price since 2015 could be possible to lead to the competitiveness with the final price per liter of bioethanol.
18 In this sense, the selling price is a crucial driver for biofuel policy to encourage the willingness of the consumers to choose
19 renewable energy over fossil fuel. Similar outcomes were remarked in the SWOT analysis by Chanthawong et al. for the case

1 study of first-generation bioethanol production, mentioning that the price fluctuation of input materials was indicated as a
2 weakness in the bioethanol policy development [37].

3 One of the economic mechanisms to support the market of low carbon fuels is to initiate the carbon pricing system on
4 fossil fuels [135]. This strategy could bring successful results in many countries to stimulate the consumption of biofuel and
5 reach the CO₂ reduction goal from fossil based fuel consumption [135]. However, it was assessed that the carbon tax imposing
6 on fossil fuel should be introduced as financing for biofuel consumption in order to stimulate the biofuel penetration in the
7 market [136]. Thailand is one of the countries where the enforcement of carbon taxation has been under consideration. Ministry
8 of Natural Resources and Environment of Thailand proposed instruments, such as the carbon taxation or carbon pricing system
9 in Climate change master plan 2015-2050 [137]. Until now, Thailand has embarked on the experiment as a pilot project, which
10 has been launched to exercise the carbon trading scheme among industries, public and private sectors [138].

11 However, the concept of levying carbon pricing or taxation on fossil fuels has been investigated to have an impact on
12 higher products price; hence it would also affect the higher expenditure for the household [139]. The conceptual idea of carbon
13 pricing for fossil fuel and the taxation to the vehicles has been proposed to the Ministry of Energy; however, it has not been
14 approved at the decision-making level regarding the reason that it could increase gasoline price. The controversy occurred
15 because of the concern regarding an effect on increasing commodity price that would become a burden for the consumers. This
16 has been a significant bottleneck to promote economic instruments for GHG mitigation [140].

17 Considered to be the second-highest relative weights, the factor of added value in biomass emphasized the stakeholders'
18 perception to enhance the value of agro-materials. The valorization of residual biomass has been put more effort to extend for
19 the higher valuable production system in Thailand; however, the current technologies have been majorly implemented to only
20 primary products, such as animal feeds, fertilizers [22], and fuel for combustion in the electricity generation [141, 142]. Until
21 now, the commercialization of lignocellulosic ethanol has still been doubted for the competitiveness with fossil fuel due to the
22 production cost. Nonetheless, it was proposed for a feasible commercialization model by developing the ethanol production,
23 along with biorefinery products [28], which would be a motivation to extend the value chain of agricultural products and
24 promote the agricultural residues for the bioeconomy development [29].

25 Next, the main-criteria of environmental impacts was the second most significant dimension, while the net energy balance,
26 which is one of its sub-criteria, was voted to be the third-highest criterion of overall relative weights. Not only does the
27 definition of this criterion have a boundary in environmental terms, but it is also related to technical feasibility, which can
28 guarantee the energy gain from a whole process [104, 143]. As the assessment of the net energy ratio of the agricultural residues
29 in cellulosic ethanol production has been verified for positive values, the potential of production technology and environmental
30 benefits have been indicated. Nonetheless, different types of raw materials associated with various numbers of net energy
31 balance and CO₂ emission. Subsequently, selection for optimal input materials would be benefit for an analysis for to lessen
32 the level of life cycle greenhouse gas [104, 143].

1 Regardless of the preferred aspect that the environmental impacts were highly ranked as the second priority, the factors
2 of land use change and GHG balance did not stand out at the top ranking of overall sub-criteria scores. Significantly, the criteria
3 regarding indirect land use change gained relatively low recognition from the governmental sectors, which are the key players
4 in the policy-making process. Currently, deforestation still has been remarked as a constant issue [144]. Despite the fact that
5 there is a forest preservation law in Thailand, namely Forest Act, B.E. 2484 [145], the land use for the agricultural industry still
6 affects food crops cultivation areas [144]. Moreover, sugarcane and rice farms burning are continually happening, causing
7 severe air pollution [146]. It can be assumed from the results from the current study that the evaluation on the matter of indirect
8 land use and GHG emissions from the plantation are unfamiliar fields for the policy-makers. As the study by Chanthawong et
9 al. has pointed out the results from the survey study that cultivating land expansion could be one of the solutions for agricultural
10 improvement for future scenarios [37]. Nonetheless, the land expansion and appropriate land use for cultivating energy crops
11 remain an issue that needs to be clarified at the policy-level.

12 Meanwhile, the technical feasibility was voted as the third-ranked dimension. The scores for this criterion were mostly
13 given by experts from academic/research institutes who hold background knowledge mainly in technology and project
14 management, and from NGO/NPO with backgrounds in energy policy and agricultural production. Among the studied criteria,
15 the biomass availability was ranked at the fourth important of overall relative weights. However, this criterion is also a critical
16 factor for bioenergy promotion in Thailand, along with the importance of economic feasibility and environmental impacts
17 because it refers to the capacity and potential to develop productions from a stable supply [147]. Spatial data with the density
18 of available biomass would indicate the potential areas and optimal production scale [148], which also influences the economic
19 analysis. This factor is considered to be a key driver in decision-making for project implementation [149].

20 The surprising outcome was the weight of social impacts as ranked at the fourth concerning dimension. Based on this, it
21 is possible to illustrate that the awareness for the local benefits has not yet risen enough in the stakeholder's perspectives.
22 According to the study of conventional ethanol production from sugarcane, the socio-economic advantage was elucidated for
23 thriving the local economy on account of laboring employment and rural incomes [129]. However, from the results of the
24 criteria evaluation in this study, job creation was the least concerning factor. The underlying background is regarded as the fact
25 that the jobs in the agricultural sector in recent years have become less popular because of lower income in agriculture
26 comparing with non-agricultural works [150]. One of the causes is considered that sugarcane and cassava cultivations are
27 heavily influenced by the weather conditions and the traditional agricultural system (e.g., monoculture system) [150]; hence
28 the farming job is volatile in terms of income from unpredictable productivity.

29 Not only the issue concerning fewer farmers working in agriculture, but unimproved production yields of sugarcane and
30 cassava could also be reflective feedbacks from the bottom-up assessment, which could draw awareness from the policymakers.
31 Projecting for long-term sustainable development, it is necessary to address the investment of infrastructures, adequate
32 irrigation systems, and technology for mechanizing agriculture to achieve higher value-added products. These are essential

1 elements to transform the agricultural sector to the higher-level industry, as advised by the stakeholders in the supplementary
2 remarks, and could also, in turn, endorse employment in this sector.

3 From the additional indicators, as voted in this study, the governmental subsidy was the most additionally selected criteria.
4 This implied that energy policy or energy-related initiation relied heavily on the economic aspect, as the subsidization or price
5 incentive is the driver to be launched by the nation. In a sense, this result emphasized an essential role of government to
6 incentivize biofuel system promotion. Thus far, the government incentive has been located at only the retail level by inducing
7 the cross-subsidization scheme, subsidizing the biofuel selling price from non-blended fossil fuel selling [133, 151].
8 Nevertheless, considering the farmers' benefits, the price guarantee system for feedstocks providers or crops growers has
9 remained concerned [147].

10 The utilization of cellulosic residues in the biorefinery for further products is a possible option to increase alternative
11 incomes for the farmers and more channels to develop the higher-skilled labors in the agricultural sector [152]. One of the
12 potential scenarios is the promotion of utilizing regional biomass, which could encourage mixed feedstocks, providing the
13 possibilities to facilitate biomass handling and logistics [72]. Furthermore, as of the technological development corresponding
14 to added-value and co-products, the end-products could be extensively recommended for biochemical production. One of the
15 backgrounds is that the bioeconomy market is transforming over time, encouraging the biomass conversion technology to be
16 established for a broad range of biorefinery products, which can be a plus for the industries to have more flexibility [153].

17 Even though the commercialization of second-generation bioethanol as an emerging technology still needs advancement
18 from the private and research sectors, the participants have agreed that the policy mechanisms and regulations by the
19 government are the necessary tools for long-term policy promotion. Especially from the governments and policy-makers points
20 of view, the preferable concerns were focused on economic feasibility and environmental impacts. It can be summarized that
21 in line with the verification on technological feasibility, the mechanisms from the government policy as well as the law and
22 regulations are the keys to facilitate the technology developers and other relevant stakeholders to achieve the profitable
23 investment and enhance the competitiveness in the market.

24 The findings highlighted the importance of financial feasibility and environmental impacts from the overall results of the
25 prioritization. However, with respect to the results, it is also likely to determine that there are no significant differences between
26 the four main-criteria. The priority would not be equal, but the evaluation should not focus on only one dimension. Regarding
27 the fact that there is no perfect bioenergy strategy that would fit all requirements [55], the results as obtained from this study
28 might be used as the initial step to developing second-generation bioethanol. Particularly, due to a long term field burn severity
29 as seen in Thailand, the first focus that needs to be dealt with is the environmental aspects regarding the pollution from field
30 burning, which could be promoted to deploy the unutilized agricultural residues. This perspective scenario is believed to be an
31 opportunity for developing lignocellulosic biomass to promote the bioeconomy and mitigate environmental impacts.

32

1 Conclusions

2 A development plan of bioethanol in Thailand has been promoted initially to substitute the imported fossil fuel and
3 encourage agricultural crop production in the energy sector. However, biofuel production has focused very little on the aspects
4 of socio-economic impacts and environmental side effects. In order to create a sustainable framework to meet the goal of
5 bioethanol production and ensure the long-term benefits for related stakeholders, the multidisciplinary dimensions and criteria
6 have become more necessary to be incorporated in the policy-making.

7 The participatory evaluation through the Delphi-AHP approach has accomplished the main objective of the study to
8 prioritize the criteria for second-generation bioethanol development. The Delphi survey process verifies the advantage of
9 anonymity in the survey conduction, which encourages the respondents to share their opinions openly. At the same time, the
10 AHP technique has proved a convincing performance in transforming the subjective opinions into multi-criteria prioritization,
11 which enables the present study to obtain the most reflective indicators representing transdisciplinary perceptions of experts.
12 Even though the scattered perceptions from different backgrounds are commonly noticeable, the Delphi-AHP technique could
13 reduce conflicts and provide agreeable results by the consenting process.

14 The findings from the study of criteria prioritization demonstrate the stakeholder's priority towards new generation
15 bioethanol, suggesting the key indicators to be taken into consideration when putting the advanced technology forward to policy
16 implementation. As a result, it is confirmed that the economic feasibility is the essential aspect of project analysis. Especially,
17 the terms of the final selling price of bioethanol and improvement of the added value of raw materials are the keywords to focus
18 on commercialization and policy recommendation. Even though the second-generation bioethanol technology is currently at
19 the level of demonstration, indicating that comprehensive understandings about the technology are yet required, environmental
20 and economic benefits are verified to be concerned factors in addition to demonstrating the technical feasibility.

21 The application of AHP did its work to reflect the perceptions regarding current concerns and the prospect of scenarios
22 suggestion, which can be compatible with the future biofuel development in Thailand. The outcomes from the current analysis
23 are believed to be references for creating a second-generation bioethanol analysis framework as a future step. With the
24 integration of multi-dimensional perspectives from stakeholders, it is possible to construct an effective process for bioenergy
25 policy to be consented by the stakeholders and attain the GHG mitigation goals, while the tradeoffs could be minimized.

26

1 Supplementary information

Delphi-Survey Questionnaire - the Prioritization of Criteria -

1. General information *

1.1 Name

1.2 Job Position

1.3 Organization

1.4 Email

1.5 Types of organization

- Governmental, ministry Policy maker
- Industry/ Business sector
- Non-Profit Organizations (NPOs) or Non-Governmental Organization (NGOs)
- Academic or research Institute
- Financial Institution or Bank
- Others

To which area fits your expertise/profession?
(You can select more than one option)

- Energy policy
- Agricultural production
- Biomass management or biomass conversion
- Bioethanol or biofuel production
- Renewable energy development or energy management
- Technology development or project development
- Environmental impacts analysis
- Socio-economic impacts analysis
- Business analysis or investment
- Economic or financial analysis
- Bioeconomy development
- Others

2

4. Part I: Prioritization of the main criteria

Question: How should we prioritize the relevant aspects?

Main Criteria	Priority Scale																		Main Criteria
	Extremely		Very Strongly		Strongly		Moderately		Equally		Moderately		Strongly		Very strongly		Extremely		
Economic Feasibility	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Technical Feasibility	
Social Impacts	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Technical Feasibility	
Environmental Impacts	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Technical Feasibility	
Social Impacts	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Economic Feasibility	
Environmental Impacts	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Economic Feasibility	
Environmental Impacts	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Social Impacts	

3

5. Part II: Prioritization of the sub-criteria

Please rate the importance of criteria considering each dimension.

5.1 Technical aspect

Question: How do you evaluate the technical feasibility?

Main Criteria	Extremely	Very Strongly	Strongly	Moderately	Equally	Moderately	Strongly	Very strongly	Extremely	Main Criteria
Ethanol productivity	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Biomass availability and collectability
Biomass logistics	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Biomass availability and collectability
Biomass logistics	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Ethanol productivity

5.2 Economic aspect

Question: How do you evaluate the sub-criteria for economic feasibility?

Main Criteria	Extremely	Very Strongly	Strongly	Moderately	Equally	Moderately	Strongly	Very strongly	Extremely	Main Criteria
Final price per liter of ethanol	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Net Present Value
Added value of input materials	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Net Present Value
Added value of input materials	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Final price per liter of ethanol

5.3 Social impacts

Question: How do you evaluate social impacts?

Main Criteria	Extremely	Very Strongly	Strongly	Moderately	Equally	Moderately	Strongly	Very strongly	Extremely	Main Criteria
Food security	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Job creation
Household income	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Job creation
Household income	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Food security

5.4 Environmental aspect

Question: How do you evaluate environmental effect?

Main Criteria	Extremely	Very Strongly	Strongly	Moderately	Equally	Moderately	Strongly	Very strongly	Extremely	Main Criteria
Greenhouse gas balance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Indirect Land Use Change (ILUC)
Net energy balance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Indirect Land Use Change (ILUC)
Net energy balance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Greenhouse gas balance

1

6 PART III : Suggestion for further criteria

In this step, the participants are able to, additionally, select further relevant criteria, if the above criteria are insufficient. Please select the additional important indicators

- Dependence on subsidy
- Distributed income
- Fertilizers or pesticides
- Water management and irrigation systems
- By-products
- Material balance
- Technology readiness level
- Air pollution level (e.g. PM 2.5, PM 10)
- Output wastes
- Land prices
- Job quality
- Forest areas

Other possible criteria

1

Please give us further comments or suggestions regarding the Delphi-Survey or the study.



Thank you for your precious time to complete our survey.

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1 **Abbreviation**

2 GHG: Greenhouse gas emission; COP21: The twenty-first session of the Conference of the Parties; AEDP: Alternative Energy
3 Development Plan; SDGs: United Nations Sustainable Development Goals; EU: European Union; MCDA: Multi-criteria decision
4 analysis; AHP: Analytic Hierarchy Process; NPV: Net present value; IRR: Internal rate of return; iLUC: Indirect Land Use; NER:
5 Net energy ratio; C.I.: Consistency Index; C.R.: Consistency ratio; R.I.: Random index; NPO: Non-Profit Organization; NGO: Non-
6 Governmental Organization; SD: Standard deviation

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11 **Ethics declarations**

12 **Ethics approval and consent to participate**

13 Not applicable

14 **Consent for publication**

15 All authors consented for this paper to be published.

16 **Competing Interest**

17 The authors declare no competing interest.

18 **Availability of data and materials**

19 The datasets generated and analyzed during the current study are not publicly available due to agreement of anonymity with
20 the respondents and privacy information concerns. However, they are available from the corresponding author on reasonable
21 request.

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5 **Authors' contribution**

6 P.J. and A.B. conceived the presented ideas. P.J. contacted the experts, conducted the survey, and executed data analysis. A.B.
7 and D.T. supervised and edited the production of the manuscript.

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Figures

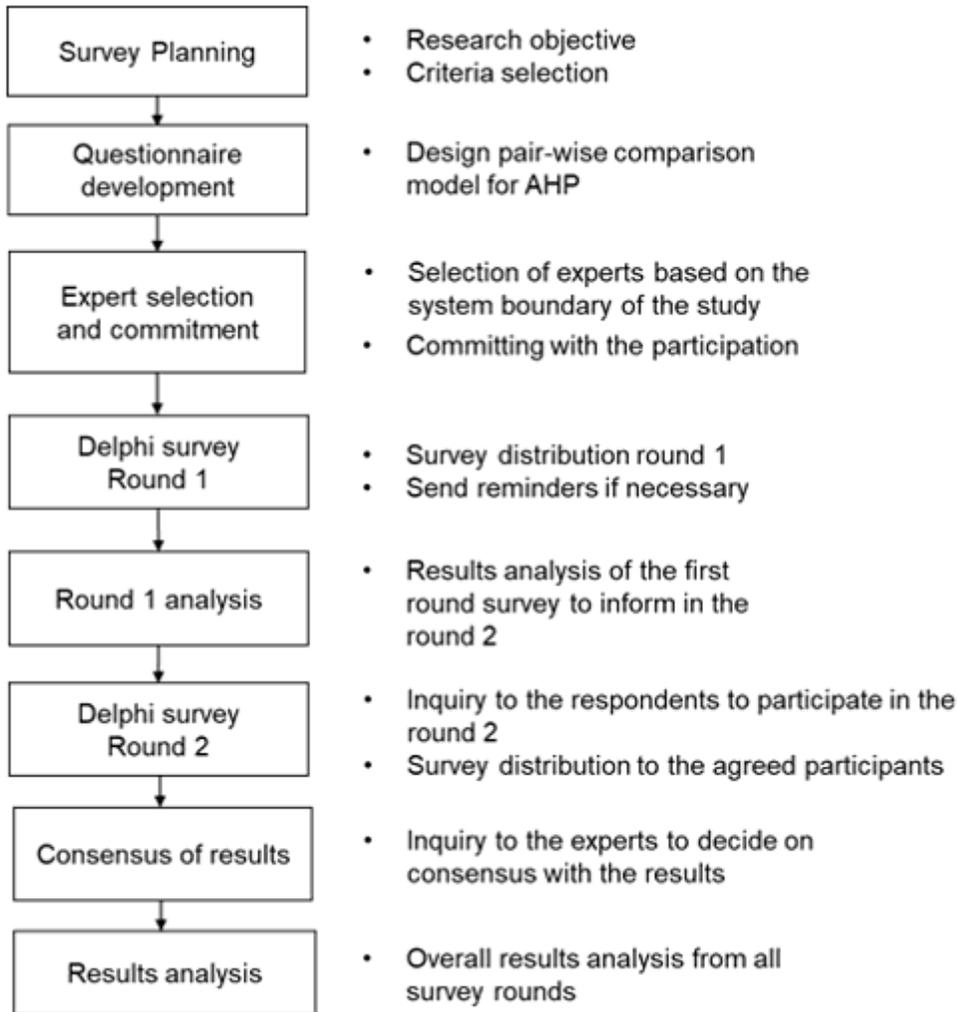


Figure 1

process flow of the current study

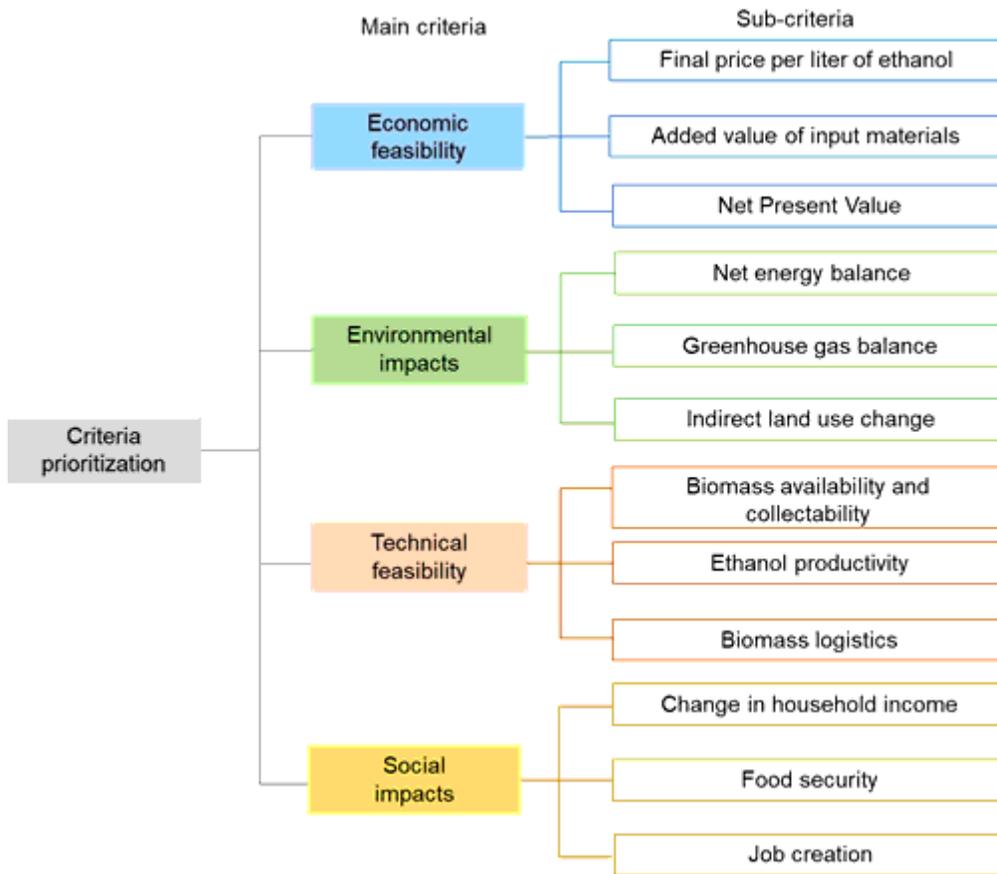


Figure 2

Hierarchical structure of selected main criteria and sub-criteria

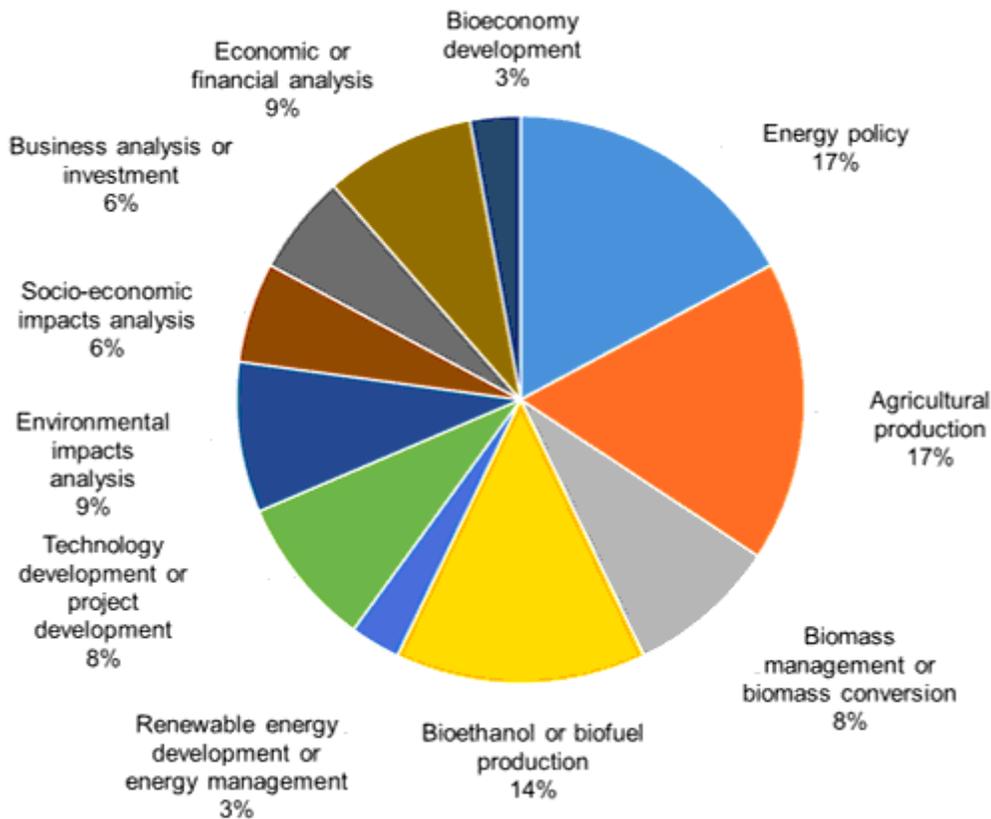


Figure 3

Proportions of areas of expertise in a group of participants

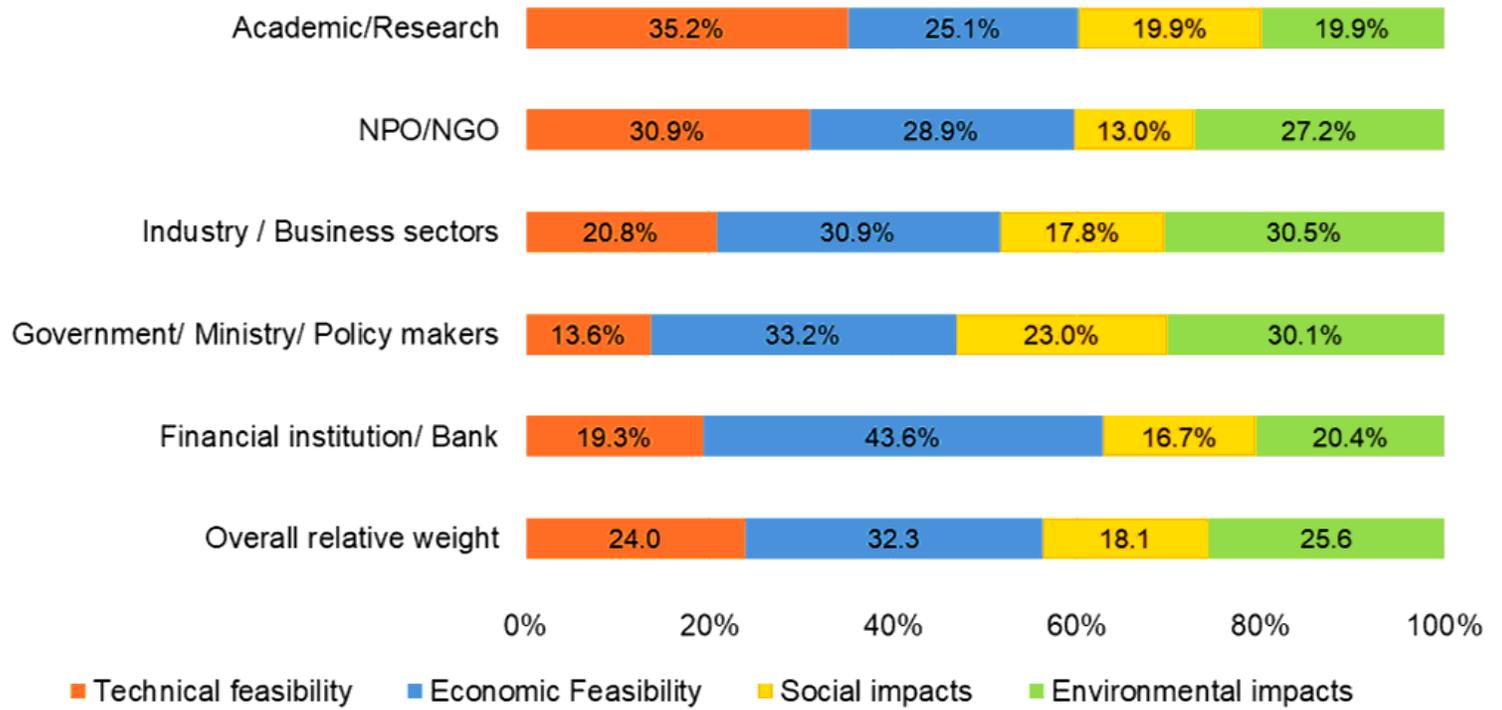


Figure 4

Main criteria prioritization divided by types of organizations and overall scores from all participants

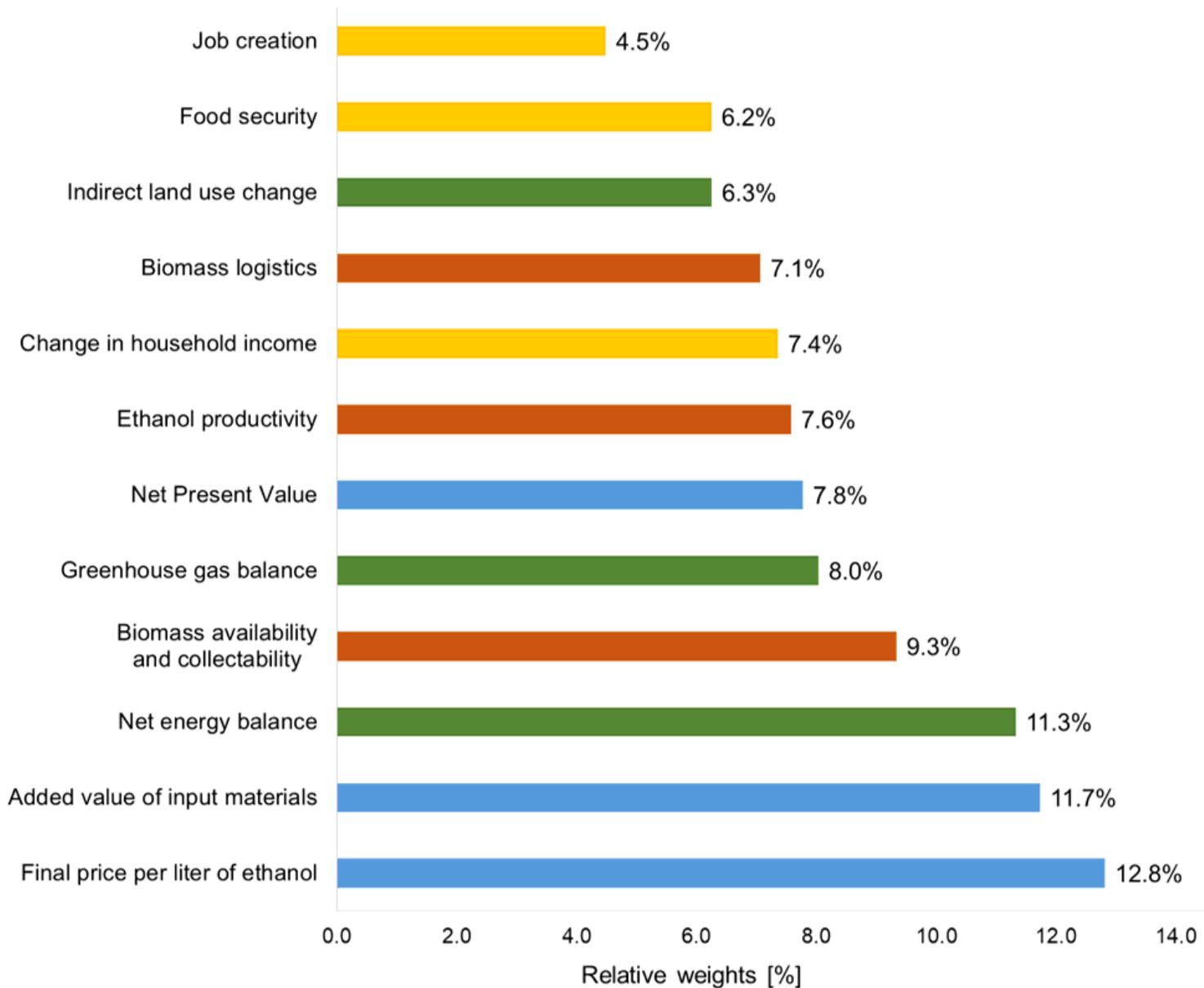


Figure 5

Range of relative weights in each sub-criteria

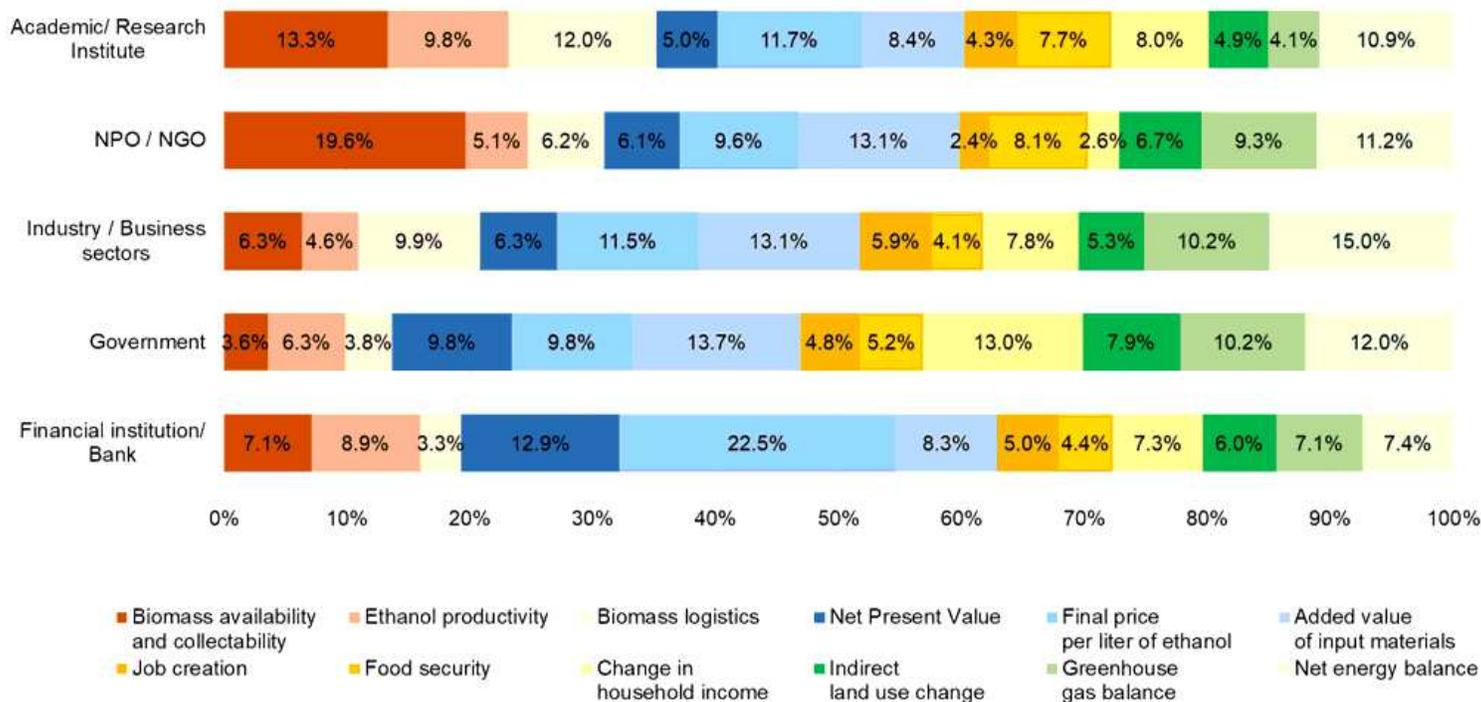


Figure 6

Relative weights for each sub-criteria as categorized by stakeholders in this study

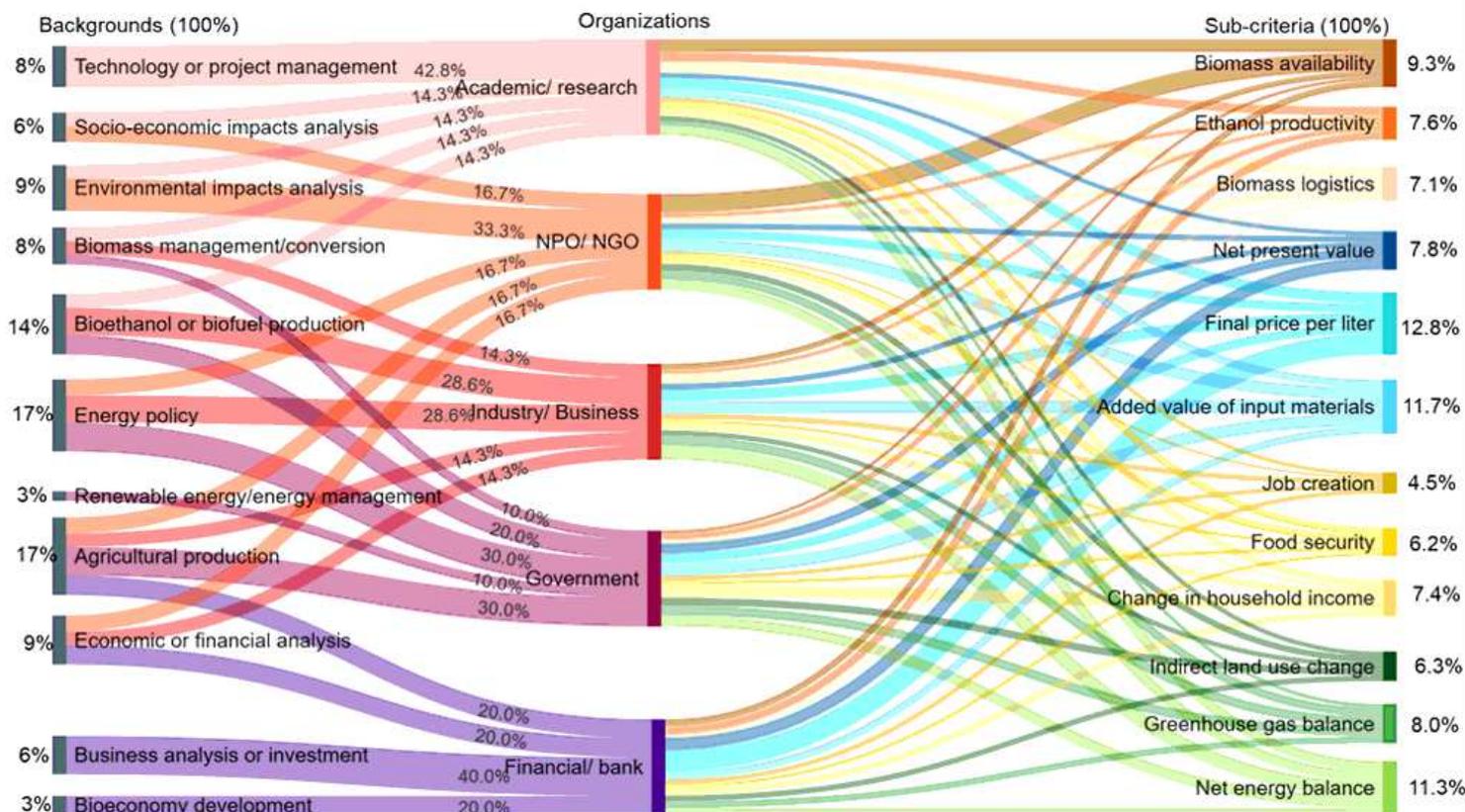


Figure 7

Sankey diagram for illustrating the relationship between the categories “Field of expertise”, “Type of organization” and “Criteria weights” as derived from the Delphi-AHP results

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [SupplementarymaterialPiradeeJusakulvijit.pdf](#)
- [Table1.xlsx](#)
- [Table2.xlsx](#)
- [Table3.xlsx](#)
- [Table4.xlsx](#)
- [Table5.xlsx](#)
- [Table6.xlsx](#)
- [Table7.xlsx](#)