A research and technology valuation model for decision analysis in the environmental and renewable energy sectors.

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1. Introduction

Investment in research, development and innovation is critical to for companies to stay competitive in medium and long term. This is particularly true for those in technology-driven sectors, such as pharmaceutical, environmental or renewable energy industries. For these sectors, the risks associated with expending resources to develop new and successful products are significant. These risks are linked to the requirement for extensive time and resources necessary to convert a good idea into an innovative product [1]. Furthermore, the resources that companies manage, both in human and economic terms, are dwarfed by the extensive resources that could be expended on potential R&D projects [2]. Thus, it is critical that project managers and decision-makers in industry have the appropriate tools required to decide where to devote these limited resources [3]. Decision analysis and valuation methods represent important tools that help managers to maximize financial returns on investments and guide the selection of critical variables during the different development phases of R&D projects.

R&D projects within a company can be monitored through different qualitative and quantitative methods as described by Ruegg [4] and Souder [5]. While R&D management through valuation models are well described in a number of journals, techno-economic valuation approaches for R&D are applied mostly in large companies and not so often in small enterprises or large academic projects. Most models, regardless of the underlying methodology used, are focused on measuring the economic return on investments. However, as stated by Davis and Owens [6], these models are most useful for providing insight into a given process, rather than by providing a final overall value for returns.

Currently, the three most widely used models are: 1) discounted cash flows (DCF), which enables the measurement of a net present value of the investment (NPV); 2) the tree decision model; and 3) real options valuations. There are other methodologies, such as system dynamics or data envelopment analyses, that are no longer widely used in industry.

Companies within the pharmaceutical sector have used the above-named valuation methodologies extensively, particularly due to the historical importance of R&D in this sector. Other sectors, such as infrastructure or energy, where R&D has not been historically so important, are now developing appropriate tools to guide sustainable business models. Not surprisingly, these sectors are adopting models developed originally by the pharmaceutical sector. Nonetheless, these methodologies are not yet, in general, used on a regular basis due to their lack of transparency or suitability. Hartamann and Hasaan [7] stated that a number of companies rely on the traditional deterministic NPV model despite its lack of flexibility, because managers feel more comfortable with the logic behind the model.

To improve the evaluation of R&D projects within the energy and environmental sectors, the ARDV model (applicable R&D valuation model) a flexible valuation methodology based on decision analysis, NPV analysis, Decision Tree Analysis and Monte Carlo simulation is presented here. This novel evaluation approach is intended for use by project managers and decision makers to simulate the stepwise progress of R&D projects and to provide a transparent model, that is free of 'black boxes', and that can be used and understood by most stakeholders. The approach that has been developed takes into account technological and commercial risks associated with launching innovative or new products into the market.

Although considerable research and theory into the valuation of commercial projects exists in the renewable energy sector [8–11], the literature is limited to the analysis and valuation of a few specific R&D projects. The approach presented in this article was developed, validated and used for several years in a company within the renewable energy sector. Although it was used within this sector, the model may also serve as a useful decision analysis tool for other capital-intensive sectors, such as infrastructure or conventional energy for medium-long term development projects (ie, projects that span from 5 to 10 years in duration).

The model presented here helps to advance current valuation models, and therefore R&D management, through a methodology that was developed to address the weaknesses of traditional models. For R&D project managers, the model provides a simple and user-friendly interface that can be adapted to a myriad of project milestones—thus, providing a clear advantage over DCF. Furthermore, the new model serves to limit risks, and enables analysis typically done with Real Options models, while providing implementation methodology and quicker analysis of results. With respect to Decision Tree Analysis, the new is model easier to implement, while covering the same number of scenarios. The model allows one to measure the impact of changes to on the overall final result—making it useful for defining project targets. Therefore, this new model represents a useful decision-making aid for managers—one that can be used over the entire lifetime of a variety of R&D projects.

The article is divided as follows: in Section 2 article, a literature review is presented that describes the current state-of-the-art in R&D valuation, and the reasons why a new model has been developed. In Section 3, a detailed description of the model methodology is presented. Section 4 presents a case study and justification, and Section 5 includes a discussion and conclusion, which summarizes the new model and describes future research trends in the area of R&D project valuation.

2. Literature review

R&D management is a relevant field in business development, and one of the main topics within R&D management is valuation. R&D valuation is an essential part of any management system and is widely used by corporations that invest in innovative projects [12]. However, the financial value of technology development is quite difficult to estimate, especially during the earliest development stages [6]. Given this uncertainty, it is not surprising that there exist inherent risks for the use of any valuation models, as they may provide misleading readouts and/or lead to incorrect conclusions [13]. The fundamental purpose of a valuation model is to provide accurate data to decision-makers and to decrease uncertainties and risks. In order to achieve goal, better models are needed [10,14]. Furthermore, models must consider that the majority of the value derived from an R&D project is, typically, generated not after initial investment, but rather via subsequent opportunities that arise thanks to this investment [15].

R&D valuation can be used over a wide range of scenarios and project types. Therefore, one must differentiate between valuation of a specific and independent project and valuation of a larger project portfolio. The latter is used to evaluate a set of independent projects that compete for the same resources within the same organization. Furthermore, decisions regarding R&D in a corporation are influenced by different factors; in addition to established valuation protocols; public policies and macro trends are also important players. Although similar methodologies can be used to analyze independent projects and a portfolio of projects, the approach taken to analyze the results should differ [16].

While other models focus only on one endpoint—the commercialization of the technology under development [13,17,18]—the literature generally agrees that the best way to value and manage R&D projects is to divide projects into different stages [19]. This approach helps to reduce risks and hedge uncertainty. The model that has been developed here is focused on project-based valuation—an approach that is also compatible with portfolio analysis. As presented by Raynor and Leroux [3], the flexibility provided by portfolio valuation, while representing a best practice for R&D projects, also enables project selection to be better aligned with the strategic goals of the organization.

As stated above, NPV, Decision Tree Analysis (DTA) and Real Options are the methodologies most often used in R&D valuation models. Because each of these have pros and cons, current research is focused on finding ways to robustly integrate them to leverage individual strengths and overcome limitations. As specified by Managi [20], the paths taken by R&D projects are highly variable; thus, models need to be flexible enough to consider various scenarios, while remaining reliable, understandable and efficient. Another important characteristic of an R&D valuation model is that, in addition to technology risks, it must also consider market risks [17]. Use of these models by managers must leverage the ambiguity typically linked to long-term R&D projects [21], and managers should carefully set strict thresholds so as to not artificially increase the project value [19].

The key limitations of the deterministic NPV model consist of the lack of flexibility and inability to adapt to the intrinsic uncertainty of R&D projects [21,22]. The NPV model relies on a series of deterministic cash flows, which are modified by a risk rate provided by a discount rate. These values are used to calculate the net present value of the investment. It has been demonstrated by several authors [23–25] that the use of a classic or deterministic NPV model, without flexibility, fails does to capture all of the potential value that a R&D project may create. Additionally, Lee [26] affirms that in the face of market uncertainties, policy changes or market disruptions, the NPV method fails to adequately describe reality.

Lint and Pennings [21] do not recommend use of NPV for long term R&D projects. Uncertainty in R&D must be seen as an opportunity and accounted for in the model [13]. To adequately manage uncertainty using the NPV model, several authors recommend the use of Monte-Carlo simulation [8,27,28].

Another commonly used methodology is Real Options (RO). It was first introduced by Myers [29] to evaluate R&D projects, and this approach has superior flexibility than previous valuation models. An added benefit provided by RO is the ability to consider future opportunities that arise from R&D project investments. It is based on financial options methodologies, defining an option as “right, but not the obligation”[13]. Many authors purport that RO best reflects flexibility [30], and the reality of an R&D project [31]; accordingly, it is the most cited model in the literature [22]. As such, RO is seen to be superior to traditional NPV in that it is better equipped to describe and account for volatility, long timelines and high-risk projects; that said, it should be noted that some RO valuation models are actually based on NPV approaches [32]. Limitations of RO have also been described [19], including the tendency to overvalue the projects due to subjective forecasts.

However, and as stated by Luo *et al*. [19], although RO is considered a more effective model than DCF and DT for R&D project evaluation, it is not widely used by the industry [22,33]. Other authors have stated that use of RO alone is not sufficient for R&D projects [10]. This may stem from serious usability issues, which have been raised by Dater *et al*. [34]. In particular, the volatility parameter, which strongly influences the final result, is the least understood and is often miscalculated [35]—effectively becoming a “black-box” for users.

Other RO limitations include the fact that the quality of RO analysis may be compromised by faulty interpretation of results and that the model has a tendency to overvalue future benefits [15,36,37]. Because of these limitations, some experts recommend combining NPV with RO when evaluating R&D projects [20].

A third model used to evaluate R&D projects is DTA. This model presents a number of future scenarios that are associated with certain probabilities [38]. A key limitation of the DTA is that it can quickly become too complicated when the number of future possibilities increases [39–42].

In order to select an appropriate model, certain experts suggest that the choice should depend on the intended final users. For example, some authors affirm that DCF is preferred by practitioners, while RO is more useful for early stage projects [17].

As summary of the advantages and limitations for the different valuation methodologies are shown in Table 1.

	Advantages	Limitations	References
Discounted Cash Flow Model	Easy to understand	Deterministic	*Lint and Pennings 1998*
	Widely use and accepted	Lack of flexibility	*Pertlizt et al .1999*
	Financial	Sensibility analysis	*Lambert 2015*
			Lee 2011
Real Options	Flexibility	Not understandable	*Hunt et al. 2003* *Oriani Sobrero 2008* *Bednyagin & Gnansounou 2011* *Luo et al. 2008* *Schachter & Mancarella 2016* *Datar & Mathews 2004* *Diesel et al. 2009* *Tompkins 2002*
	Uncertainty	Inefficient	
	Financial	Complicated data implementation	
		Result interpretation	
		Project overvalue	
Decision Tree Analysis	Graphical representation	Difficult implementation	*Wang & Halal 2010* *Trigeorgis 1997* *Vega-Gonzalez & Rivera-Velasco 2016*
	Simple analysis for few scenarios	Sensibility analysis	
		Complexity for significant number of scenarios	

Table 1 Advantages and limitations of existing valuation methodologies.

Of all the different industrial sectors, the pharmaceutical sector is the most developed in terms of R&D valuation [7,28]. Within the renewable energy sector, although there are intensive R&D investments, there are a paucity of studies that explore sector-specific case studies or scenarios [9]. Thus, it is clear that there is a need for more research into the area of renewable energy valuation. While the models have been developed via macro comparisons with fossil fuels [43], and studies have defined market potential [44] and utility of the inclusive willing to pay methods [9], existing sector-specific models have serious limitations [24].

To solve these hurdles, this article presents a flexible, user-friendly and understandable model that reflects the intrinsic risks associated with R&D projects, while highlighting the main technological developments needed to achieve economic and commercial viability, the ARDV Model. The ARDV model, in addition to prioritizing projects based on economic returns, can be used to rank projects by the difficulty of achieving technical targets.

3. Model explanation

R&D project valuation, particularly in the renewable energy sector, must consider the following issues: i) uncertainty inherent in the development of the technical aspects of the project; ii) long-term market conditions and risks associated with market acceptance; and iii) maturity of R&D project. The model presented here covers these three issues.

In order to take into account inherent uncertainty, the ARDV model considers variables that serve to faithfully describe key technical characteristics of the R&D project. From our experience, it is recommended that no more than five technical variables be analyzed per project. This number sufficiently serves to describe the evolution of the project and allows good correlation between variables, while enabling the effective interpretation of results, such as, the price of the raw material vs. the final product cost. Selection of these variables and the values introduced for each must be agreed upon by the project technologists and other project participants [21].

Market drivers are as important as technology variables. Selling prices, market regulations, the numbers of potential business opportunities are included in the model. Furthermore, the influence of competitors on the selling prices and market share are modeled. As with the technical variables, correlations between these variables can be modeled. Moreover, correlation between technical variables and market variables can comprise part of the model.

Because uncertainties in an R&D project are significant, the selected variables are modeled using Monte Carlo simulation with different probabilistic curves. To define the curves for each variable, the user can draw on the range defined for each and set the probability that the value of a variable is at the minimum, maximum, as well as the mode and/or the average in a previously defined range. The dispersion of the inputs introduced in the model is a function of the maturity of each of the variables. This data is used to create the most likely curve for the variable; possible curves can be either continuous (beta, normal, triangular, etc.) or discrete (binomial, discrete, etc.). This methodology then enables the future behavior of the project, and consequently the inherent risk, to be defined and projected for the R&D project.

The period considered for market commercialization of a technology is also important. This period depends on the technology and market maturity, and it is defined as the obsolescence period, which is the duration of time over which new technologies remain competitive in the market. This period varies depending on the technology and according to market conditions; namely, the number of competitors and entry barriers. In our model, the duration of market commercialization spans between 7 and 20 years.

One of the main challenges to creating a reliable model is the need for realistic inputs for the variables. Market variables are taken from reports by prestigious agencies that publish future trends in the renewable energy sector, such as the International Energy Agency or the Energy Information Administration. Technical variables are defined based on the current state-of-the-art and theoretical values and technological objectives for each of the projects.

Once the inputs and associated uncertainties are introduced, the model is ready to evaluate the viability of the technology. However, additional information is required to take into account potential market opportunities and the number of facilities to be executed thanks to the R&D development.

The energy and environmental markets offer limited opportunities for new technologies. To help identify these, the product pipeline under evaluation is introduced into the model and is based on forecasts provided by international agencies and internal companies' predictions. For some projects, a probability of occurrence of the market opportunity is included. As it is often the case, a number of additional opportunities, which have not been identified originally in the pipeline, may ultimately arise.

In order to make the value calculation, the model simulates a project for each of the opportunities that may appear in the pipeline and it calculates the cash flow for each. After satisfying the cash flow and the investment criteria, which in our case is set as a minimum internal return rate (IRR), if the project fulfils the requirements defined by the firm, then the project would be executed and consequently will generate value for the company.

But the model is not just a go/no-go decision model, it also enables analyses of the main variables required to reach a viable product within the technical and economical realms. The model can also enable users to discern critical variables and identify where more resources should be invested based on their ability to influence economic returns. Furthermore, the model can be used to define a path between various technical targets for each phase, and to review these paths and how they influence other variables and projected economic returns.

For any economic valuation, the accuracy and quality of financial parameters are critical. As explained above, while ARDV model is a techno-economic model, it is also focused on studying the viability of R&D projects, so the discount rate cannot be calculated only based on financial parameters, as some authors affirm [35]. To evaluate R&D projects, companies generally use the weighted average cost of capital (WACC), which has been traditionally used for commercial projects—an approach that is likely not appropriate [27]. Taking this into account, for R&D projects, the discount rate should depend on factors, such as project sector, the maturity of the project and the target market. For the current model, project maturity is the most weighted factor.

The company where the model was validated is managed using the 3H methodology introduced by McKinsey in their publication “The Alchemy of Growth”[45]. Using this methodology, a project is divided into three categories or ‘horizons’ depending on their role in the organization. Briefly, these are: H1 – the cash generators; H2 – growth options; H3 – future options. To ensure a balanced R&D project portfolio, there should exist a spread of these three horizons to ensure that new and innovative products are developed, while maintaining cash generation. Obviously, each horizon is associated with a different level of risk, both technological and commercial, and this must be considered in the discount rate. Typically, the discount rate range used in our model operates within the following ranges: H1 (7 – 9%); H2 (10 – 12%); and H3 (12 – 15%). The exact numbers chosen within these ranges depend on the specific project characteristics and those of the sector and market maturity, etc. The methodology of the current model is presented in the next section using a specific example.

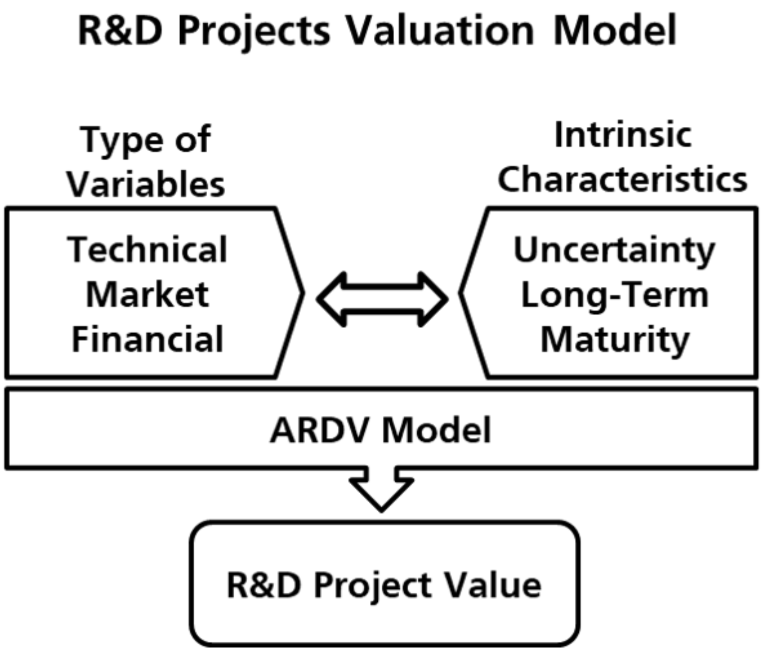

Figure 1 Graphical abstract: valuation decision model graphical abstract

4. A case study and justification

Below is described a detailed example in which the ARDV model was used to valuate an R&D project. The model has been validated through its use in a multinational company that is focused on the engineering and construction of renewable energy projects with proprietary technology. The company, which has its headquarters in the South of Spain, had (in 2015) a presence in more than 70 countries and more than 20,000 employees worldwide. The company has a strong innovative culture and is a pioneer in commercializing new technologies in biofuels, solar or hydrogen energies. It owned the first commercial solar tower in Africa and the biggest thermal solar complex in Europe. The company understood the food versus fuel dilemma and promoted research in the area of bioethanol from agricultural residues and municipal solid wastes.

The company invested nearly €100 million in R&D in 2014. This R&D was organized according to the different sectors in which the company had a presence: bioenergy, solar, water, hydrogen and power electronics. Each of these sectors run their own projects under a project director and a number of project managers that handle the allocated funds.

The case presented in this paper was set in the bioenergy area, although the project includes a combination of energy and environmental activities and involved second generation (2G) biofuel production. One of the key goals of 2G technology is to produce biofuels from agricultural residues, which is currently in early stages of commercialization [46]. In this case, the raw material that is used to produce fuel is municipal solid waste (MSW). The impetus for this project was based on the fact that almost all of the ethanol produced for blending with gasoline is derived from cereal grains or sugarcane.

The project addresses an emerging issue regarding MSW—the sheer volume of it is becoming a problem for municipalities worldwide and one that is expected to worsen as the world population increases [47,48]. In summary, the R&D project under evaluation in this example involves the production of bioethanol from MSW in order to aid the treatment of MSW and to generate a biofuel. Figure 2, below, provides a high-level overview of the process of producing ethanol using MSW as raw starting material.

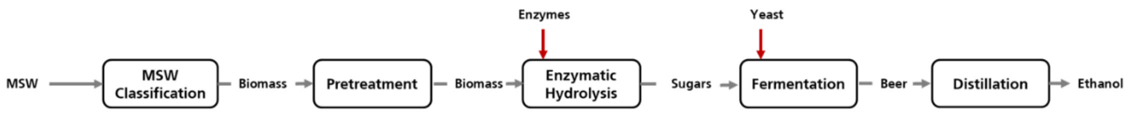

Figure 2. High-level process configuration for the production of Ethanol using Municipal Solid Waste (MSW) as raw material.[1]

The obvious first step required to build the model is data collection. This step can be divided into three main areas: technical inputs, market inputs and financial hypothesis. The second step is to select the main variables that influence the technical development of the R&D project. The critical technical variables are selected by the project director and should include all variables that impact commercial viability, should not be more than five in order to ensure that analysis of the data is feasible. Namely, for this project, these variables are; i) ethanol yield per

[1] The figure shows the main steps in the conversion of MSW into ethanol. The first step is pre-sorting the MSW; in the second step, the organic fraction is sent for pretreatment and enzymatic hydrolysis, during which the enzyme cocktail is added. The sugar produced in during hydrolysis is fermented to produce the beer that is distilled to obtain ethanol.

ton of raw material, ii) natural gas consumption, iii) enzyme dose, iv) and capital expenditure (Capex).

Ethanol yield per ton of raw material serves as readout of improvements made to the pretreatment of the starting material; it measures the amount of product (ethanol) that can be obtained per unit of raw material (ton of MSW). The natural gas consumption is the main expense in the operation of the plant, or the main variable cost; thus, reducing this value will directly benefit the profitability of the process. The performance of 2G ethanol technology depends heavily on enzyme performance [46], which is the enabling additive that transforms the raw material into a viable product. The Capex, which measures the funds needed to be financed per project, is a critical determinant of financial viability.

As described in the previous section, each of the variables are defined by a range and a trend that models how they change as the project progresses. These values are defined by considering acceptable parameters for current state-of-the-art processes and the technological objectives of the project.

Process improvements arise from two main factors: the R&D activities, and the learning curve, which defines the incremental improvements made as projects are successfully commercialized and scaled up. However, both sources of improvement are uncertain; thus, in order to include this in the model for each of the selected variables, a value range is defined. Table 2 shows, on the one hand, how the variable ranges change based on the number of plants built, termed the learning curve (see the various columns in Table 2). On the other hand, Table 2 also shows the ranges of each variable, which depend on success of the R&D project. The project director is the person in charge of defining these ranges, in accordance with the project targets.

Number of Facilities Constructed	1st Facility		2nd and 3rd Facility		4th to 15th Facility		Facility >15	
Critical Technical Variables	Probability	Value	Probability	Value	Probability	Value	Probability	Value
Natural Gas Use (MW)	15%	18	25%	18	25%	15	40%	15
	60%	21	60%	21	60%	18	50%	18
	25%	24	15%	24	15%	21	10%	21
EtOH per raw material (gal/Ton MSW)	20%	65	15%	65	10%	65	10%	65
	60%	75	70%	75	80%	75	80%	75
	20%	85	15%	85	10%	85	10%	85
Enzyme Dose (mg/g)	10%	12	10%	10	5%	9	15%	9
	30%	15	40%	12	15%	10	60%	10
	60%	18	50%	15	80%	12	25%	12
CapEx (M€)	10%	260	20%	260	50%	260	80%	260
	55%	311	60%	311	40%	311	15%	311
	35%	350	20%	330	10%	330	5%	330

Table 2 Technical variables to be included in the model.[2]

For each of the above variables, the most accurate probabilistic curve is defined, thanks to a software model known as @Risk. As an example, a curve for natural gas consumption in the first facility, as shown in Table 2 above, is presented in Figure 3.

[2] The first column indicates the model's technical variables. The rest of the columns are variable ranges and probabilities depending on the number of plants built.

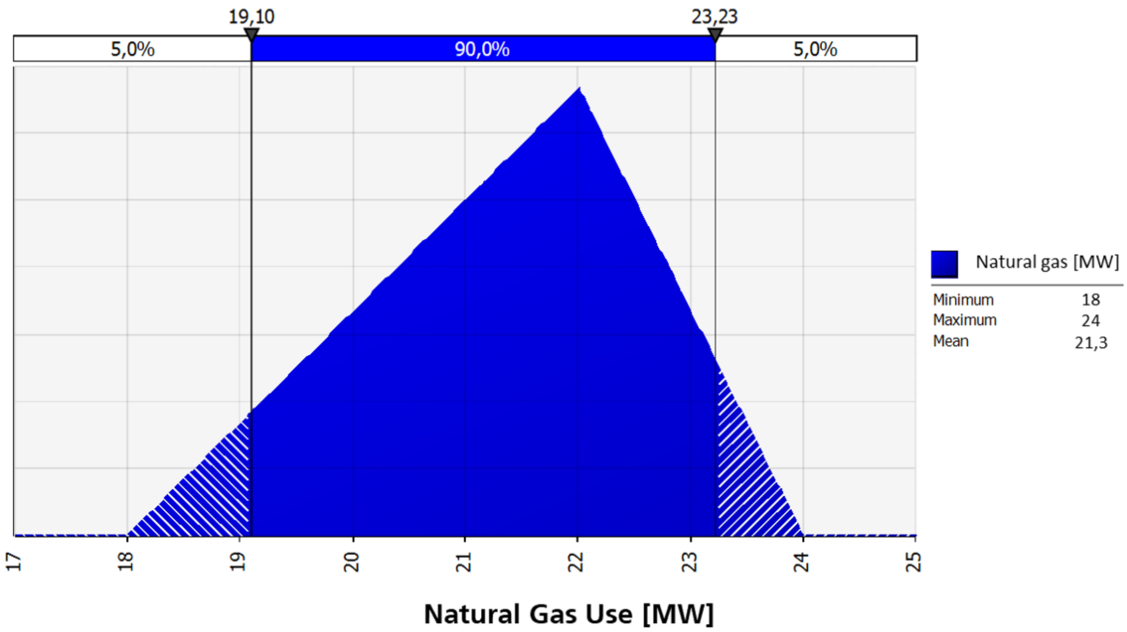

Figure 3 Probabilistic curves for natural gas consumption. The area cover by the figure fulfils 100% probability for the analysed variable[3].

On the market side, the methodology is similar. In this case, three variables that are most likely to influence commercial viability were selected. These variables are selected by the project director, who has most in-depth knowledge of the project, and by the corporate strategy department of the company, which is responsible for providing market know-how and defining prices (ie, a market analysis expert).

The variables that were chosen were: i) the price of ethanol; ii) the fee that the company would charge municipalities per ton of MSW treated; and iii) number of industrial plants that will ultimately use the commercialized technology. Regarding ethanol price, four scenarios are defined in the model. These scenarios are based on projected legislation changes, the company's past experiences and the existence of

[3] The figure shows the graphical representation of the evolution of the Natural Gas (NG)

subsidies for advanced biofuels. The scenarios shown in Figure 4 correspond to the future price ranges provided to the model.

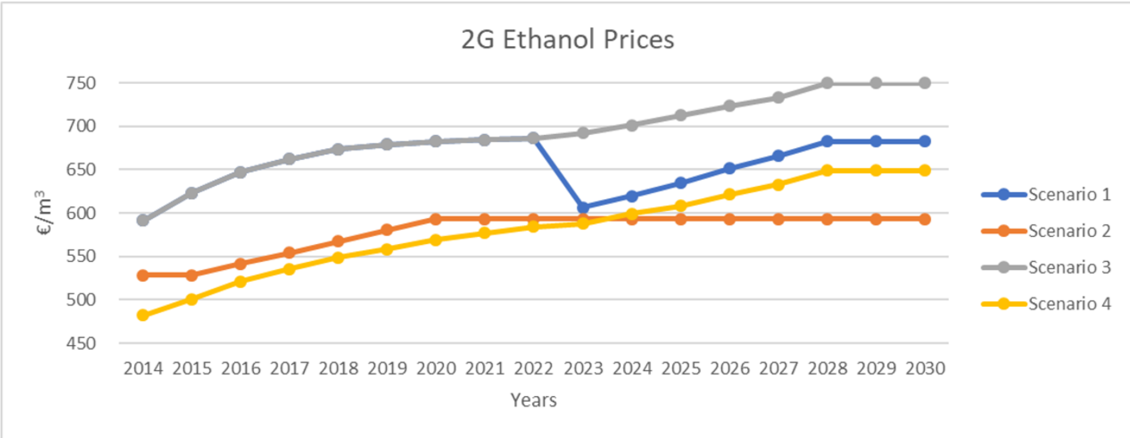

Figure 4 Ethanol prices.[4]

The second variable, which is critical to the success of the project, is the fee that the company would charge municipalities per ton of solid waste treated. This is a competitive market where companies develop new technologies to fulfill the prerequisites set by municipal administration, in terms of prices and environmental requirements. It is expected that the fee paid by the municipalities will decrease in coming years, mainly because incoming technologies will further increase the competitiveness of the market. As with the other variables, probabilistic curves were inputted into the model based on internal company projections. Table 3 shows the MSW fee range; also, note that as the number of facilities increase, competitiveness is expected to increase and the fee paid by the municipality thus decreases.

[4] All the scenarios are internal predictions made by the company. Scenario 1: High oil prices and fiscal credit till 2022; Scenario 2: Internal company strategic plan; Scenario 3: High oil prices and fiscal credit extended beyond 2022: Scenario 4: No fiscal credit since 2014.

Number of Facilities Constructed	1st Facility		2nd and 3rd Facility		4th to 15th Facility		Facility >15	
Critical Marlet Variables	Probability	Value	Probability	Value	Probability	Value	Probability	Value
MSW fee (€/ton)	0%	30	0%	30	2%	30	35%	30
	0%	40	8%	40	17%	40	29%	40
	12%	50	11%	50	21%	50	22%	50
	20%	60	18%	60	23%	60	9%	60
	50%	70	45%	70	24%	70	5%	70
	18%	80	18%	80	13%	80	0%	80

Table 3 MSW fee. The table shows the evolution of the MSW fee variable.[5]

A third key variable is the number of industrial plants that will ultimately use the technology. The potential market readout slowly grows from the start of the commercialization process up until the end of the 20 years period (ie, the obsolescence period) (Figure 5). The project pipeline is based on internal company projections. Each opportunity is defined for the municipalities worldwide that have shown interest in building a facility with these characteristics.

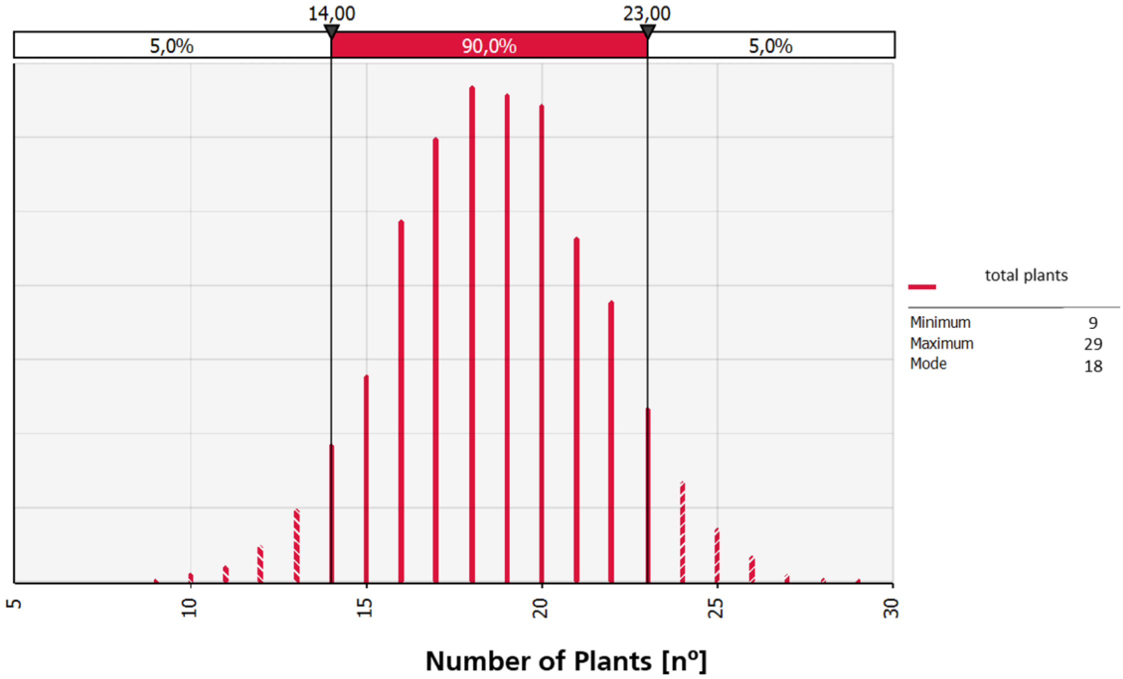

Figure 5 Number of commercial opportunities in the next 20 years. The graphic shows the probabilities of plants of being built in the valuation period. Each project in the pipeline has a probability of occurrence. The sum up of each number of plants fulfils 100% probability for the analysed variable

[5] The columns are the ranges of the variables and probabilities depending on the number of plants built.

To the above project variables, we shall ad the financial parameters to measure the project, which will be influenced by the maturity of the project. As explained in the previous section, the maturity of the technology is the factor that most influences the financial parameters used. The maturity of this project is considered to be ‘H2’ (as per McKinsey Methodology [45]) in terms of a R&D project, due to the fact that the technology has already been demonstrated at bench scale, but not at the commercial plant scale. The return rate required (IRR) for this kind of project ranges between 8% and 10%. For this specific project, a value of 8% has been chosen for the first two plants and a value of 10% has been chosen for subsequent plants. This was done to take into account the greater risks associated with the first plants to be developed, while ensuring that investor margins were not overvalued at early stages and to enable the technology to become commercial though requesting lower returns.

Once all the variables were inputted and defined, the model provided a cash flow model per year from 2016 to 2029 for each project, including the option to consolidate all of the projects. This last readout is critical, as it enables the user to identify the total amount of resources required and the cash recovery.

<u>Results</u>

The first set of results presented below is for the evaluation of a stand-alone plant. Subsequently, the evaluation of all R&D programs is shown, including the calculation of overall development cost.

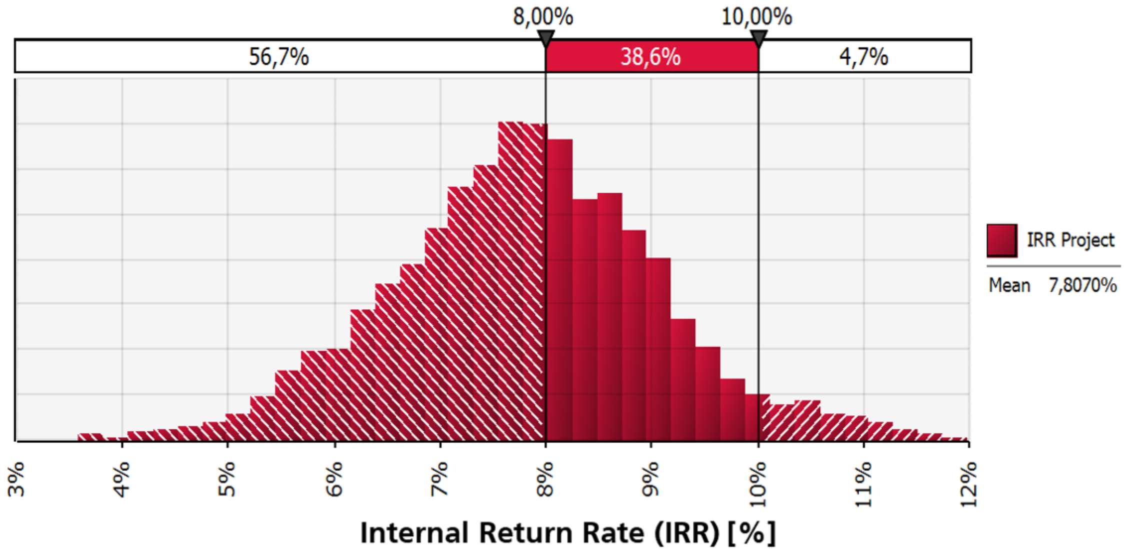

Figure 6: IRR for the initial facility. The area cover by the figure fulfils 100% probability for the analysed variable [6]

The first analysis reveals that in aproximatley 45% of the simulated cases the IRR will be greater than 8%, which provides the go ahead for constructuion of the plant. While the model is useful for calculating the probabilty of positive returns, it can also be used to inform the project team about how to influence these forecasted results. To gain this insight, the user must identify which variables exert the greatest influence on the final IRR of the projet. This can be achieved by carrying out correlation analysis, which reveals the relationship between IRR and key influencers.

[6] The graphic shows the IRR distribution for the first commercial plant built. With a probability of 43.3% the IRR of the plant will be above 8% and only in the 4.7% of cases will the IRR be above 10%.

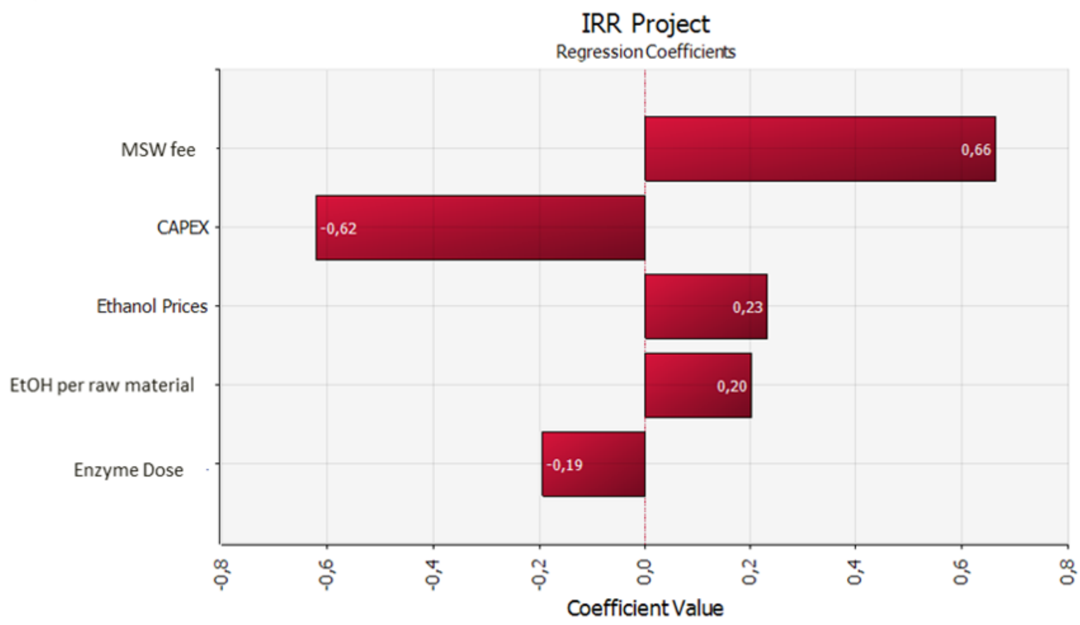

Figure 7: Sensibility analysis.[7].

The first variable is a market input—specifically, it is the fee that is charged per ton of MSW treated. While the leadership overseeing R&D has limited ability to influence this variable, the risks associated with it must be carefully considered and be used to determine which markets are targeted. The second variable is CaPex (Figure 7). Typically, every R&D project that enters into the last phase of development must concentrate their efforts on improving process design in order to reduce the required investments.

The third variable is the 'potential to ethanol', which is related to two factors: the quality of the starting raw materials, which varies according to geography (note: discuss this factor it is not further discussed because it does not influence model outcomes); and how the raw material is pretreated (a variable that the model shows directly affects economic returns).

[7] The sensibility graphs show that the variable that most influence the model is the MSW fee while Enzyme Dose has much lower effect. If the MSW increases it has a positive effect on the IRR, on the other hand if the CAPEX increases it has a negative effect on the IRR.

Yet another market variable is ethanol price. This must be carefully considered as it will greatly impact whether the project achieves commercial success.

The last variable that was considered is enzyme dose. The model shows that this variable has a similar impact as the 'potential to ethanol' and also that reductions in the dose will positively impact outcomes (Figure 7).

After this initial analyses, and by considering how the variables influence each other and the outcomes, the developers can then decide on which variables they want to focus.

Construction of subsequent facilities

After analyzing how R&D improvements differentially influence the IRR for the first facility, further analysis was conducted for the construction of subsequent facilities. In Figure 8, the change in IRR over time is shown; the graph shows that the R&D and construction of new plants improves returns, until the number of facilities is above 15.

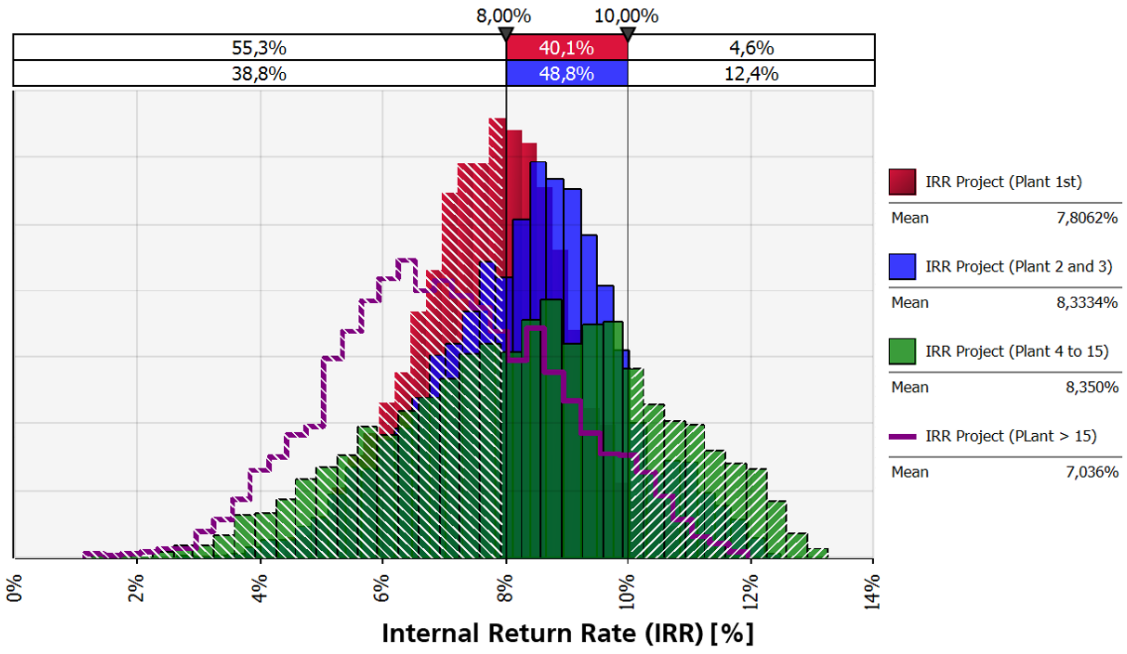

Figure 8: The evolution of IRR as the project matures. Red graph: 1st plant to be built; Blue graph: 2nd and 3rd plants. Green graph: 4th to 15th plants and Purple line plants > 15. The area cover by the figures for each of the scenarios (1st plant, 2nd and 3rd plant, 4th to 15th plants and plants>15) fulfils 100% probability for the analysed variable.

While this seems counterintuitive, it is hypothesized that as the number of plants increase, the market becomes saturated, and consequently the fee per ton of MSW will decrease enough to offset any gains made due to technical improvements.

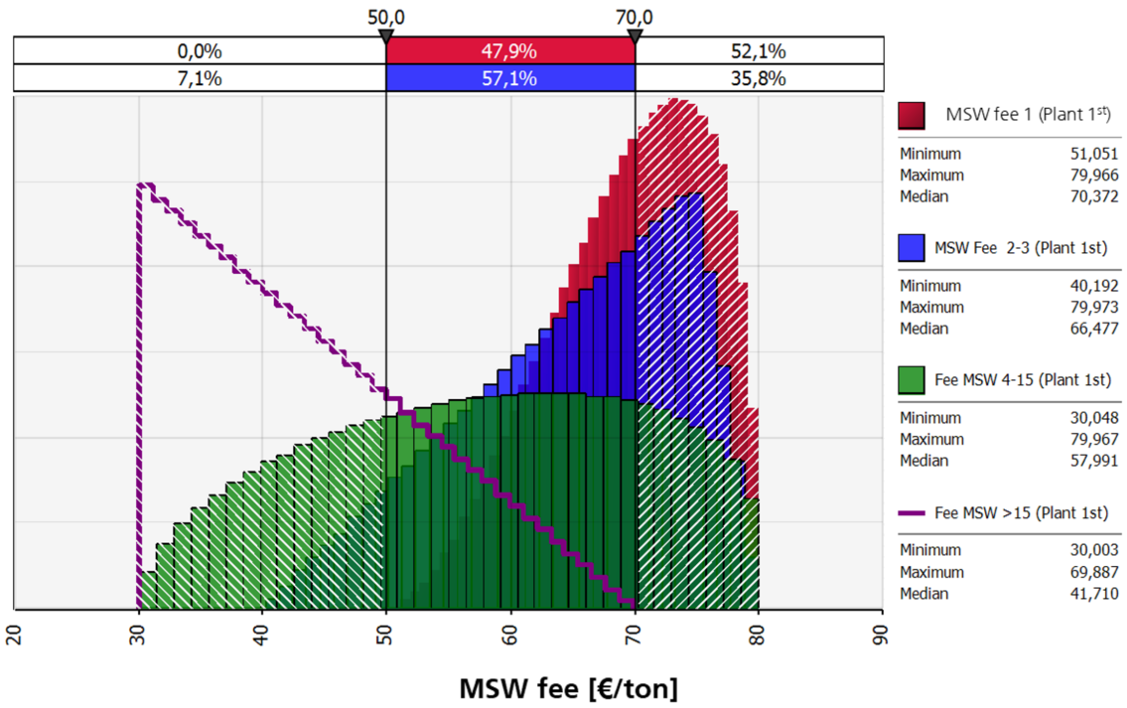

Figure 9: Hypothesized effects of changes to MSW fees. Red graph: 1st plant built; Blue graph: 2nd and 3rd plants. Green graph: 4th to 15th plants and Purple line plants>15. The area cover by the figures for each of the scenarios (1st plant, 2nd and 3rd plant, 4th to 15th plants and plants>15) fulfils 100% probability for the analysed variable.

Considering this data, it is key to determine the minimum fee per ton of MSW that the project requires to be viable for the number of plants to be built. The model can quickly determine this by enabling one to run the simulation while varying the value of the MSW fee. In this particular case the minimum fee required for an IRR above 8% is €49.2/ton. This is higher than the €41.7 /ton that the model gives for the point at which more than 15 plants are constructed. Thus, the model can identify key variables and threshold values required, which together help reveal a clear path towards the development of competitive products. By accounting for how the technologies evolve over time, the model also enables companies to forecast key market values to can could inform the drafting of future agreements and strategies to adapt to competitive pressures.

Program valuation

The next step in the analysis is to determine the total program return, or the total value that will be created by the R&D investment. The model helps to weigh product pipelines and project developments against the total resources needed for product commercialization—key factors that can help managers proactively adjust resource allocations as the project advances.

The model considers the fulfillment of the investment criteria for each commercial opportunity, and also the total program value creation. This latter value is determined by calculating of NPV ranges to be created for investors, while considering the discount rate. As previously mentioned, this is a techno-economic valuation; thus, it is not purely a financial analysis and, along with profitability of the R&D project, the model also aims to identify project viability from a technical perspective. As such, the discount rate is calculated based on the maturity of the project and the number of resources allocated to R&D, similarly to how the methodology is used to calculate IRR. As an H2 project, the discount rate is 10%. For other stages, such as H1, the range is less, due to lower risks (i.e., 8-10%), while values increase for higher risk H3 projects (i.e., 12-15%).

The timeline that the model considers is 15 years, which corresponds to the lifespan of the technology—a value that is determined by considering commercialization readiness, obsolescence period and the time span required to fully capture total potential value created by the technology. The R&D investment period is set to 6 years from the date of valuation.

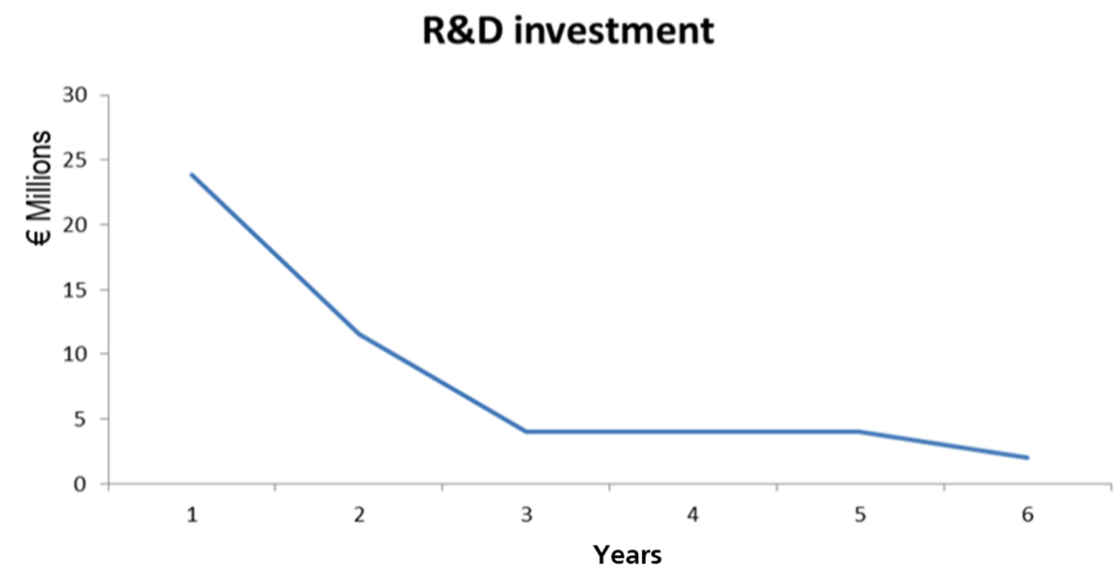

Figure 10: R&D Investment for the MSW program.

Considering the characteristics chosen above, the value generated by the total program is shown in the Figure11. The left-hand side of the graph shows that the project has a 32% chance of causing net economic loss for the company, with potential losses reaching a maximum of €34M. However, the right-hand side of the graph shows that the project has a 25% chance of generating net positive economic returns valued greater than €100M (Figure 11).

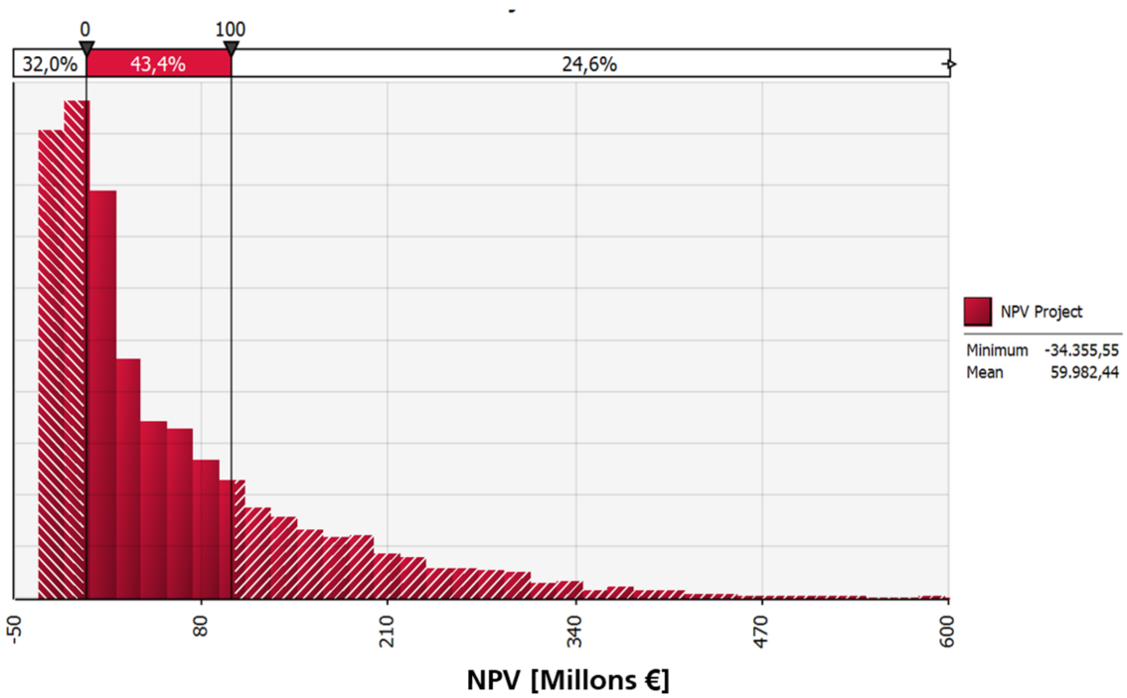

Figure 11: Program NPV. The area cover by the figure fulfils 100% probability for the analysed variable [8]

When considering risk management, managers should be constantly searching for ways to reduce the risk of losses. As described in the literature [3,16,49], R&D investments are made in phases. Thus, evaluating and optimizing risks present in each phase serves to reduce global risk—a strategy that can be followed using our model. For the current project under evaluation, our model shows that when the project is in the early stages of commercialization, an important consideration is the timing of the construction of the plant. If management sets a limit—for example, that the project be aborted if the first plant is not built within 2 years of project launch—the model shows that maximum potential losses fall to €25M; however, this policy would greatly reduce the possibility of achieving positive returns.

[8] The graphic shows the total NPV for the MSW program. The spread of the results is a consequence of the uncertainty and risks involved in the project.

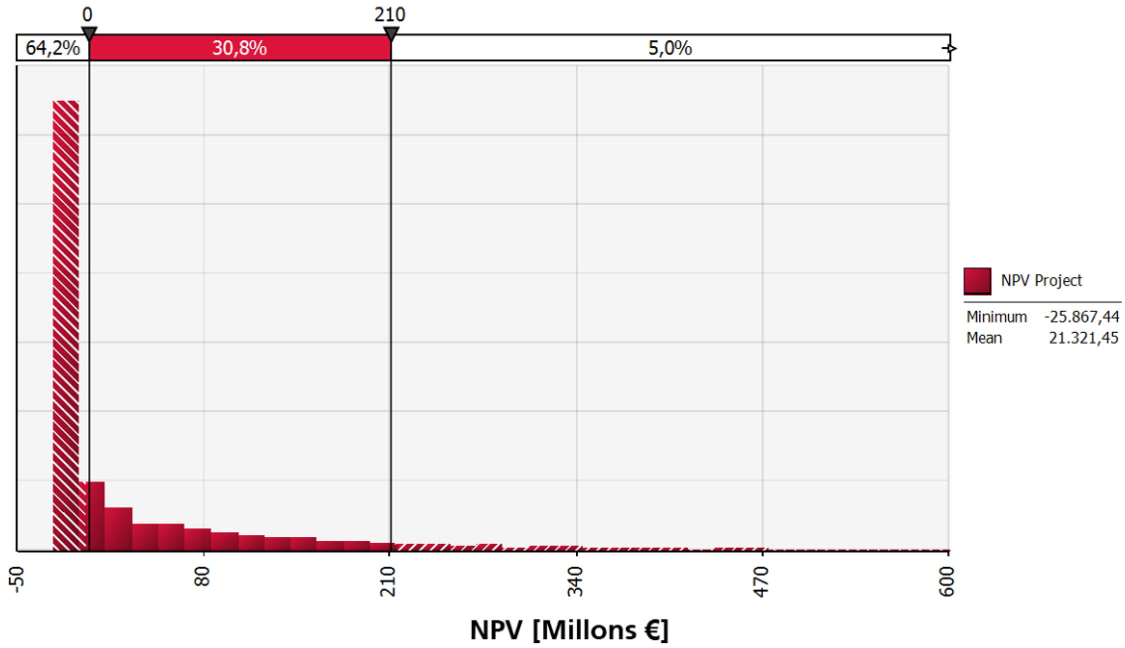

Figure 12: Program NPV limiting the R&D investment. On one hand, the NPV is affected positively due to the decrease in R&D investment; while on the other hand, the project suffers due to lack of technical competitiveness. The area cover by the figure fulfils 100% probability for the analysed variable.

This is likely because, as shown in Figure10, much of the foundational R&D investments have already been made, and as such, aborting the project reduces the possibility of recovering these investments. After analyzing the stress scenarios, it becomes clear that the proper decision is to continue the R&D project, because while the potential losses grow when the project is continued, the possibilities of receiving a positive return increase to a greater extent.

5. Discussion

There are numerous valuation models for R&D projects; unfortunately, many of them have considerable limitations [17]. This paper presents a comprehensive and robust ARDV model that displays easily interpreted graphic results. These can be used by managers and project leaders to make decisions based on data and a clear understanding of the projects implications. The tool presented in this study takes as inputs, data that project managers have obtained during the execution of the project or information that is gleaned from available data, which is more transparent when compared with Real Options models, where data implementation may become a "black-box" [30,50]. Another advantage of this new model is that the results are presented as graphical outputs that are easy to interpret and analyze. This makes the model particularly attractive for decision makers because the conclusions drawn can be understood and easily explained to the organization. For example, this is an improvement over the RO and DTA models, which provide values as readouts that can be difficult to interpret and compare to other scenarios [51,52][53]. Another benefit of our model is that it includes programs that enable managers to carry out sensibility analysis, as shown in Figure 7. Combined, these advantages enable managers and project managers to use this new model to define clear and measurable targets and gauge the impact of decision making on project progress—overcoming one of the main limitations of the classical NPV model [8,17].

Decision Analysis Model	Easy to understand
	Manager acceptance
	Flexibility
	Graphical representation
	Sensibility analysis
	Direct result interpretation

Table 4 Decision model analysis presented in this article

Although the case study described in this paper is for a project that is at an advanced stage of development, the model can be used at any R&D project stage. This flexibility represents an advantage over models that exclusively focus on early project stages [54] or mature projects [17,19]. Moreover, the valuation model can be updated as different project phases progress, so that the model evolves with the project, providing managers with an up-to-date view of the project and the ability to trace and track key decisions made during project execution. Use of the model in this way enables managers to define clear and measureable targets throughout the entire project. Thus, by 'connecting the dots' over the project lifespan, the model can be used by managers to define funds the required and expected returns based on improvements in previous phases—a characteristic that is complementary to other analyses that are focused on portfolio valuation [55].

Although this article deals with a particular example within the bioenergy sector, the model can be used in both the environmental and renewable energy sectors. It is particularly relevant for projects with medium/long term development periods (ie, about 5 years); and those with intensive capital expenditure, both at the R&D stage and at the first commercial facility (or product) stage.

It should be noted that the methodology presented in this article can be used to valuate alternatives of the final product or different projects—enabling analysis across a full product portfolio. This flexible and homogenous valuation methodology provides comparable data and results that can be used to make decisions across a product portfolio, as can be carried out using DTA [41], but with the advantage of being able to do it as part of a single analysis.

Regarding portfolio analysis in a same simulation, although the ARDV model can be used for portfolio analysis, at present the model would need to be run separately, it means in different simulations, for each of the projects, which would impy This limitation need to be overcome in future. However, the analysis and comparison between two (or more) projects is feasible and provides reliable results.

6. Conclusions

This article presents a R&D valuation model that is flexible, reliable and reflects the intrinsic uncertainty associated with intensive capital expenditure projects. The benefits of the presented model are the following:

- The model focuses on decision making analysis, which provides a better understanding of the potential returns, and the ability to gauge the effect of key variables on project development.
- The model overcomes the following existing bottlenecks:
  - It can be implemented at different project stages, from early R&D phases, when they have a lot of uncertainty, to pre-commercial stages, when the confidence increases.
  - It provides graphical outputs that are easy to understand by managers and project leaders.
  - It can be used to simulate multiple scenarios, while doing so in a way that is simple and easy to understand.
- The model can be applied to any renewable energy, environmental or conventional energy project.

Some of the current limitations of the model presented here include the following:

- Technical variables are defined by project directors; thus, if the data is not defined in a rigorous manner, the analysis could become impartial.

To overcome this limitation, a Steering Committee could be created and tasked with deciding on the inputs; alternately, forecasting methodologies, such as the Delphi methodology, could be used.

In conclusion, the valuation model presented here has the potential to become an important tool to support R&D management—one that provides complementary knowledge and confidence for making decisions under uncertain circumstances. The methodology is particularly relevant for use with capital intensive programs that require several years of development and that are executed within highly competitive technological niches and markets. Given the flexibility of this model, it can be easily adapted for valuation in other sectors or for different project types—a characteristic that overcomes the limitations of other more traditional models.

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