

Techno-economic assessment of solar fuel production

DLR process guideline



DLR

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List of abbreviations

Abbreviation	Definition
<i>ATB</i>	Annual technology baseline
<i>CAPEX</i>	Capital expenditures
<i>CCU</i>	Carbon capture and utilization
<i>CEPCI</i>	Chemical engineering plant cost index
<i>CF</i>	Capacity factor
<i>CFD</i>	Computational fluid dynamics
<i>CHP</i>	Combined heat and power
<i>CRF</i>	Capital recovery factor
<i>CSP</i>	Concentrated solar power
<i>CST</i>	Concentrated solar thermal
<i>CSV</i>	Comma separated values
<i>DHI</i>	Diffused horizontal irradiance
<i>DNI</i>	Direct normal irradiance
<i>DPP</i>	Discounted payback period
<i>EPC</i>	Engineering, procurement and construction
<i>FCI</i>	Fixed capital investment
<i>FEM</i>	Finite element method
<i>GHI</i>	Global horizontal irradiance
<i>GMT</i>	Greenwich mean time
<i>HHV</i>	High heating value
<i>IEA</i>	International Energy Agency
<i>IRR</i>	Internal rate of return
<i>LCA</i>	Life cycle assessment
<i>LCOE</i>	Levelized cost of electricity
<i>LCOF</i>	Levelized cost of fuel
<i>LCOH</i>	Levelized cost of heat
<i>LCOH₂</i>	Levelized cost of hydrogen
<i>LCOM</i>	Levelized cost of methanol
<i>LHV</i>	Low heating value
<i>MARR</i>	Minimum acceptable rate of return
<i>NPV</i>	Net present value
<i>NREL</i>	National Renewable Energy Laboratory
<i>NSRDB</i>	National Solar Radiation Database
<i>OPEX</i>	Operational expenditures
<i>OS</i>	Operating strategies

Abbreviation	Definition
<i>PPA</i>	Power purchase agreement
<i>PV</i>	Photovoltaic
<i>QFD</i>	Quality function deployment
<i>SPP</i>	Simple payback period
<i>TCI</i>	Total capital investment
<i>TEA</i>	Tecno-economic assessment
<i>TEPET</i>	Techno Economic Process Evaluation Tool
<i>TLCC</i>	Total life cycle cost
<i>TMY</i>	Typical meteorological year
<i>TRL</i>	Technology readiness level
<i>UTC</i>	Coordinated universal time

Abstract

This document serves as a guideline for the techno-economic assessment (TEA) of solar fuel production, developed to establish a structured and standardized approach for conducting analyses within this scope. In addition to its role as a methodological reference, it also functions as a key training resource for new team members, supporting their understanding and consistent application of the adopted procedures.

Its main objective is to harmonize internal processes and consolidate the documentation of best practices, drawing on decades of accumulated experience and extensive collaboration with external partners in the fields of solar energy and chemical processes. By providing a common framework, this guideline promotes efficiency, transparency, and comparability across future studies and projects.

By standardizing procedures and structuring the TEA approach, we aim to:

- Ensure transparency and traceability of main assumptions, methods, and parameters;
- Promote consistency in conducting TEA studies, enabling comparability across projects and internal assessments;
- Avoid duplication of work, thereby improving operational efficiency;
- Support capacity building by fostering the dissemination of accumulated technical knowledge.

However, it is important to emphasize that this document does not represent an exhaustive or definitive set of methods. The methodologies presented here must be applied with caution and adapted to the specific context and needs of each use-case, considering the unique characteristics of the processes analyzed, the required level of detail to ensure quality and representativeness, and the significance of the models and results. To increase the comprehensiveness of the analysis, it is also recommended to perform a life cycle assessment (LCA) alongside the TEA, providing an integrated technical, economic, and environmental evaluation of the process. While the LCA is not part of this guideline, it represents a potential area for future integration.

Although this guideline may be consulted by partners or third parties, it should be used with discretion. The practices described herein have been developed for a specific internal environment and may not fully reflect all normative, regulatory, or operational requirements of other institutions or projects. Therefore, it is strongly recommended that any adaptation carefully accounts for application-specific nuances to ensure the validity, relevance, and meaningful interpretation of results.

1. Motivation for techno-economic analysis

A techno-economic analysis (TEA) is a systematic and structured method to evaluate technical concepts from both technical and economic perspectives. Such analysis can be employed in different stages of technology development of energy systems, as illustrated in Figure 1. In a research and development context, the typical progression involves the pre-feasibility level and the feasibility level, which comes into play once a real commercial project is established. The following levels are typically used only in industry since they refer to real commercial projects close to realization. At the macro-economic level, a country-wide energy system analysis is performed using a very simplified representation of the single power or process plant.

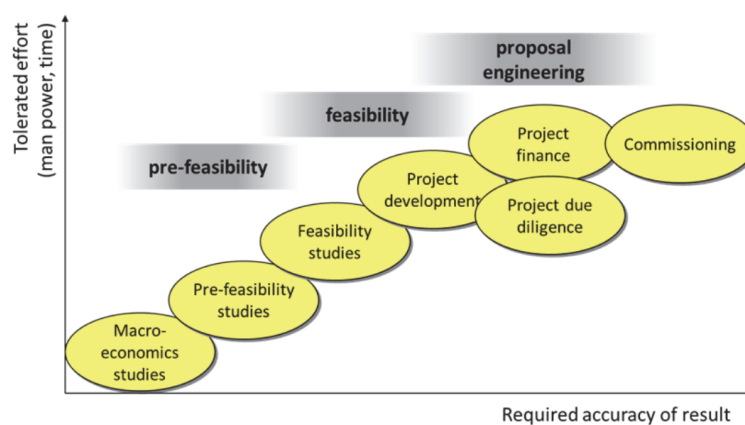


Figure 1: TEA in different phases of technology development (Hirsch, 2017).

This guideline addresses the typical applications of research, i.e. low-technology readiness level (TRL) technologies or new system layouts based on established technologies. Typically, one or more innovative concepts are compared with a state-of-the art solution, the so-called reference system. In contrast to a pure technical evaluation, e.g., comparison of cycle efficiency, the TEA also provides information on the economic potential of a technology. Yet, the challenge of a TEA for new technologies is that technical as well as economic parameters come along with significant uncertainty, since experience exists only from small-scale demonstrators. For new concepts based on established components, the challenge arises from the interfaces and the new “bundle” of components which is not established in terms of technical and economic parameters. Sometimes, even broadly accepted evaluation methods are not established, since new functionalities are added (e.g., co-production of several products, such as heat, electricity and chemicals).

Due to these challenges, it is highly important to follow a structured TEA approach that guarantees:

- Transparency on all assumptions, methods and parameters;
- Avoidance of errors and consideration of all the important aspects;
- Meaningful presentation of results;

- Correct interpretation of results;
- Repeatability of the results;
- Comparability with studies of other authors.

The presented guideline as developed by the DLR institutes of Solar Research (SF) and Future Fuels (FF), outlines and explains all relevant steps of the TEA. For the institutes, it serves the following purposes:

- Harmonization of the internal TEA processes leading to the above results;
- Avoidance of double work by setting standards and providing templates;
- Educational document for employees new in this field;
- Quality documentation for external customers and partners.

Finally, the outcomes of the TEA are compiled in a TEA report that holds all relevant information on assumptions, results, and their interpretation.

2. Overview on the TEA process

This chapter introduces the systematic steps to be followed in the TEA and provides general considerations for the TEA process. Some references are compiled to other documents that relate to the topic.

2.1. Steps in the TEA process

The TEA process described in this guideline is composed of three phases, as illustrated in Figure 2.

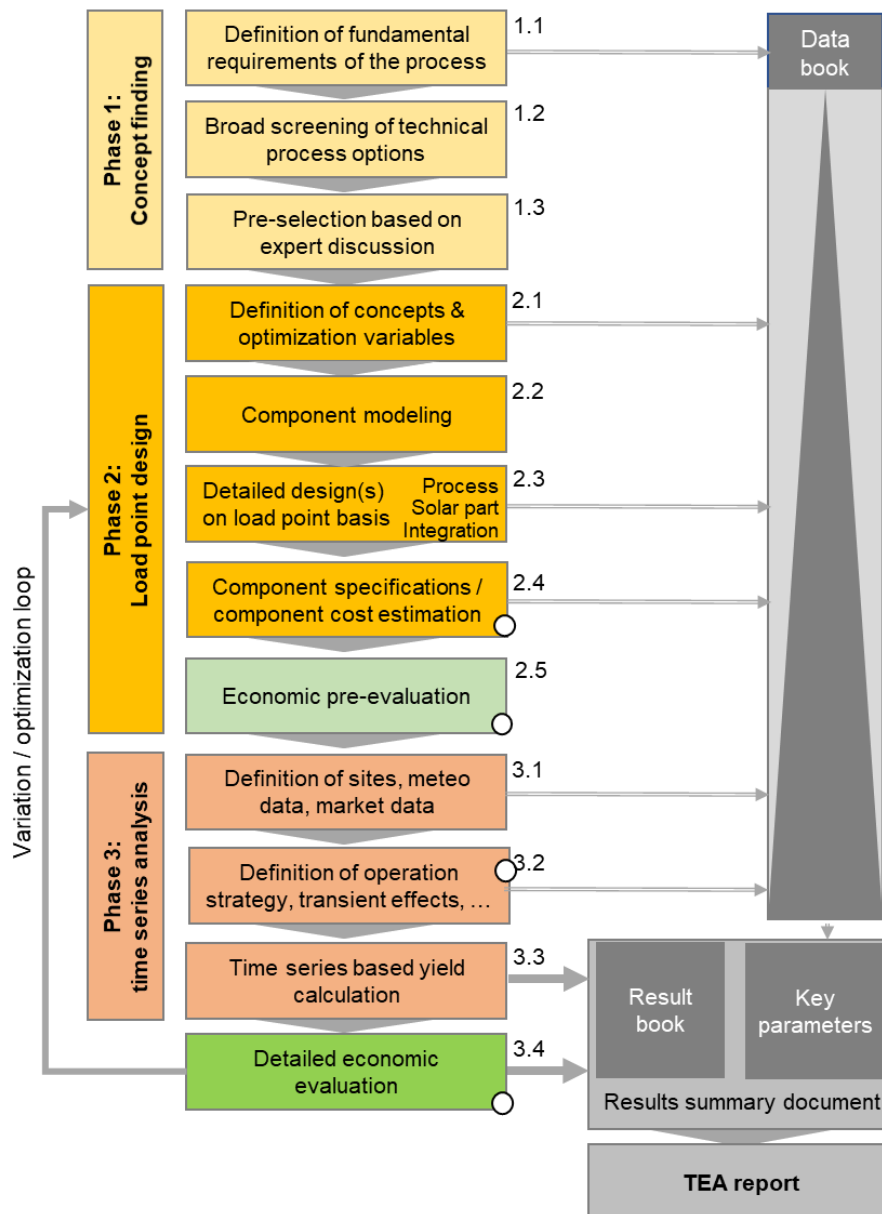


Figure 2: Phases and steps of the TEA process. The white dots indicate that at these points life cycle assessment (LCA) methods could be included in the future.

In the **Concept Finding stage (Phase 1)** the fundamental requirements for the processes to be investigated are compiled (Step 1.1). This includes e.g.:

- The definition of the product and the desired quality as well as quantity generated by the process (electricity, heat, chemicals or combinations);
- The resources that can be considered (e.g., solar, electricity from the grid, chemical educts, etc.);
- Restrictions on the technologies to be considered,
- The location(s) together with the resource and meteorological data (e.g., typical meteorological years – TMYs);
- Some indications on the criteria that are relevant for evaluation (e.g., maximum output at a specific site, lowest production costs, following certain load trajectories).

This catalogue has to be agreed on between all participating parties before it can be used as the basis of the following steps. The definition Step 1.1 is followed by a broad technical screening of potential solutions (Step 1.2). This step is crucial as it aims to consider as many solutions as possible without immediate evaluation. In order to reduce the number of concepts to be investigated in more detail, a preselection based on a set of criteria and expert input follows (Step 1.3). In some cases, the technologies to be considered may have already been preselected, allowing the work to directly proceed to Phase 2.

In the **Load Point Design stage (Phase 2)** the concepts are further detailed at least for a number of highly relevant load points of the plant. This phase reveals the technical feasibility of the concepts and leads to a more detailed set of technical parameters needed for the analysis based on time series calculations. Based on the results from Phase 1 the technical concepts to be investigated are precisely described and the set of variables that shall be used for optimization is fixed (e.g., the capacity of an electrolyzer unit can be assumed constant while the solar field size together with the storage capacity are the variables to be optimized). Also, the evaluation criteria shall be sketched already. This selection is highly relevant especially if rather different technical solutions are on the table and the comparison is complicated by diverging characteristics of the concepts (e.g., how to compare a system that produces with solar energy from the own site only with a system that generates with 24/7 electricity from the grid?). Based on these preliminary settings heat and mass flow diagrams are worked out for the systems in Step 2.2. It is usually helpful to distinguish between the design of the solar system and the design of the chemical process since specialized tools are available for each task. It is important to consider all relevant load points of the systems and the integration of solar and process plant to identify potential technical dependencies and general problems. Once the load point designs are available, a first dimensioning of components and their respective costs is possible in Step 2.3 (e.g., defining a heat exchanger based on the required temperature difference and deriving the costs usually depending on the heat exchanging surface).

For this first dimensioning, the nominal operation load point (in configurations with storage systems, charge and discharge operation) is considered. While it may not be necessary in all cases, it is feasible to conduct a first economic pre-evaluation at this stage (Step 2.4). The annual performance is estimated based on a projection of different load points to an annual sum. Since interdependencies and distinct weather conditions are not considered, such pre-evaluation can only be considered as first indication but might be used to exclude obviously non-competitive concepts from the further steps.

Finally, the **Time Series Analysis stage (Phase 3)** is dedicated to a time-series-based analysis of the concepts. In a first Step 3.1, time dependent inputs like weather data files, electricity market price series, expected load profiles etc. are defined. An important aspect is the definition of the operation strategy and the transient behavior of the plant components (step 3.2). As soon as storage units or dispatchable resources are included, it has to be decided when which unit shall operate. Once these definitions are done, the respective simulation models are set up, verified and the annual simulations are carried out (step 3.3). The annual technical simulation provides the technical results on e.g., annual basis.

This information is then combined with the economic parameters like capital expenditures (CAPEX) and operational expenditures (OPEX) to determine the economic result figures like the levelized cost of X – where “X” corresponds e.g., to electricity (LCOE), heat (LCOH), hydrogen (LCOH₂), or other fuel such as methanol (LCOF or LCOM). In order to find the best configurations (e.g., size of solar field and storage) either a certain parameter range can be scanned and the best solution picked from the results, or an optimization algorithm is wrapped around in the simulations in order to adapt the variables until the optimum is found. Since the first approach usually leads to more information on the system characteristics (e.g., dependency on storage size), this is usually the preferred approach. Although the calculation methodology can be highly accurate, it is important to consider that the uncertainty surrounding the technical and economic input parameters may undermine the precision of the optimization effort.

Along the whole process, a data book that holds all relevant technical and economic assumptions is filled and maintained. The data book together with the result book is the main content of the TEA report. Usually, all relevant result data is stored in one single file in order to allow fast access and overview on all results.

2.2. Recommendation levels *should, shall, may*

Depending on the application and required level of detail, the set of requirements has to be adapted. This avoids not suitable refinement for coarse studies as well as too simplified approaches for more detailed investigations. For a guideline document it is useful to define three levels of recommendations:

- **Shall:** these rules are the minimum requirements that are recommended to achieve a standardized TEA/LCA. Every TEA/LCA produced using these guidelines must cover these basic rules. All rules in this category have to be addressed;
- **Should:** these rules cover a recommended level of analysis and should be applied to produce a TEA/LCA of greater depth;
- **May:** use of these rules produces the greatest detail of TEA/LCA. These rules may not be applicable in all studies and should be applied as determined by the practitioner.

While the guideline focuses on establishing a standardized TEA framework, it is crucial to recognize that the specific requirements and depth of analysis may vary based on the application and objectives of the study. Therefore, practitioners should be mindful of the recommended levels and exercise their professional judgment to adapt the analysis accordingly. By acknowledging these recommendation levels, practitioners can ensure a thorough and appropriate analysis that suits the needs of their particular project or investigation.

2.3. Reference to other documents

This guideline incorporates concepts from other documents. While there is significant overlap in the general principles, specific ideas from the following documents have also been included:

SolarPACES Guideline for Bankable STE Yield Assessment, Version 2017, IEA Technology Collaboration Program SolarPACES (Hirsch, 2017)

This guideline is developed to establish high quality TEAs for solar thermal power plants. The document is the result of an international project that led to the publication by SolarPACES in 2017. Many conceptual aspects and contents for solar plant modelling are taken from this guideline:

- General concepts for systematic approach;
- Concept of time series based technical analysis (annual or multi-annual);
- Economic assessment.

Techno-Economic Assessment & Life Cycle Assessment Guidelines for CO₂ Utilization, Version 2 (Langhorst et al., 2022)

While this comprehensive guideline primarily focusses on topic of carbon capture, utilization, and storage (CCU), elements from this guideline have been used in the present work.

- General concepts for systematic approach.

The guideline has been developed in a joint effort with universities from Germany, Great Britain and the USA.

A standardized methodology for the techno-economic evaluation of alternative fuels – A case study (Albrecht et al., 2017)

The research paper published by DLR Institute of Engineering Thermodynamics (TT) illustrates the Techno Economic Process Evaluation Tool (TEPET) for evaluation of alternative fuels which has been developed at this institute. The core of this tool is the coupling of the Aspen Plus simulation tool with an economic evaluation that includes component cost estimates based on equipment cost databases and correction factors.

- General concepts for systematic approach.

Plant design and economics for chemical engineers (Peters et al., 2003)

This book covers the essential principles of industrial processes design and the associated economic analysis, offering a comprehensive overview of fundamental design parameters and decision-making techniques for the chemical in industry. Important contributions from this reference to this document are:

- General concepts for chemical process modelling;
- Economic parameters for the evaluation of chemical processes.

Chemical engineering process design and economics: A practical guide (Ulrich and Vasudevan, 2004)

As well as the previous document, this book addresses the essential methods for the design of chemical processes, with a large focus on cost analysis, equipment selection and methodologies for decision-making in the design of industrial processes. Significant inputs from this source to this document encompass:

- General concepts for chemical process modelling;
- Economic parameters for the evaluation of chemical processes.

3. Phase 1: Concept finding phase

The aim of this phase is to clearly define which technical concepts will be analyzed in more detail. Depending on the project, the concepts might already be well pre-defined or a main task is to develop suitable concepts.

3.1. Step 1.1: Definition of fundamental requirements

Before starting an investigation, it is essential to define its objective and some first boundary conditions to be considered in the further preselection of options. First definitions could e.g., refer to:

- Product(s) to be generated (e.g., main product hydrogen, methanol, ammonia; side products, cogeneration of electricity or heat);
- Interfaces to the rest of the world (e.g., can electricity be used from/supplied to the grid?);
- Technology restrictions (e.g., certain technology options to be explicitly considered or excluded);
- Location of plant (e.g., certain country, solar quality of location, soiling assumptions),
- Size/capacity of the plant or quantity of product;
- Operating strategy (24/7, solar driven, etc.).

It is also helpful to already define some first criteria for the evaluation. This can be technical and economic criteria like the levelized cost of a certain product. All definitions done in this phase shall be written down in the data book.

3.2. Step 1.2: Broad screening of options

In step 1.1 the initial task definition is followed by a broad screening of potential technical options, often referred to as a “brainstorming” session. This phase can be conducted either in a workshop involving experts or, if feasible, initiated by individuals to establish a foundation for subsequent discussions. During this process the following guiding principles should be adhered to:

1. **Avoid premature evaluation:** It is crucial not to prematurely evaluate the brainstormed options at this stage. The purpose here is to generate a wide array of potential solutions without narrowing down the portfolio through premature judgment.
2. **Systematic approach:** To maintain a systematic and organized approach, employing a matrix can be beneficial. This matrix categorizes the subsystems and their respective sub-functions. Subsequently, these elements are recombined to form new solution options. An illustrative example of this approach is provided in Figure 3.
3. **Technical sketches:** it is also advantageous to prepare technical sketches or diagrams representing the proposed plant concepts. The sketches serve to ensure that all stakeholders share a common understanding of the concepts and their differences between them.

		CSP				PV-Kombi				CSP-PV								
Comoponent		C1	C2	C3	C4	P1	P2	P3	P4	CP1	CP2	CP3	CP4	CP5	CP6	CP7	CP8	CP9
CSP	Solar field PT Oil	x												x				x
	Solar field PT Molten Salt		x												x			
	Solar field ST Molten Salt			x	x					x	x	x	x			x		no field!
	thermal storage MS	x	x	x	x					x	x	x	x	x	x	x	x	x
	fossil HTF/ steam generator	x	x	x	x					x	x	x	x	x	x	x	x	x
	Steam turbine	x	x	x	x					x	x	x	x	x	x	x	x	x
PV	kristalin module					x	x	x	x	x	x	x	x	x	x	x	x	x
	fix mounting						x				x		x					
	1-axis tracking					x		x	x	x		x		x	x	x	x	x
Battery	Li-Ion storage					x	x	x	x			x	x	opti.	opti.	opti.	opti.	x
Fossil	GT				x			x								x		
	GUD (ACC)								x									
	Motor					x	x											

Figure 3: Example of concept definition with broad screening (Thermvolt project).

3.3. Step 1.3: Preselection based on expert guess

The screening phase usually results in a large number of ideas/concepts that have to be limited to a suitable number of concepts that undergone further investigation. The following steps shall be done to come to a preselection.

Firstly, it is essential to streamline the concepts by grouping together those that are identical or closely related. This simplifies the subsequent evaluation process. Each concept should be given a distinct and meaningful name, accompanied by a unique identifier for clarity and reference purposes. To gain a clear understanding of each concept's basic functionality and, crucially, how it differs from others, comprehensive sketches or descriptions should be developed.

To facilitate the concept evaluation process, the establishment of a weighting matrix is imperative. This begins with the compilation of a comprehensive set of requirements or criteria that bear direct relevance to the evaluation at hand. Subsequently, the criteria are subjected to a weighting procedure, where their relative importance concerning one another is delineated.

This weighting procedure is conducted by examining each requirement (representing the rows in the matrix) in relation to every other requirement (representing the columns in the matrix). The analysis employs a predefined method:

- If the analyzed requirement is decisively more crucial than the compared requirement, it is assigned a weight of 4, while the compared requirement receives a weight of 0;
- If the analyzed requirement holds greater significance than the compared requirement, it is allocated a weight of 3, with the compared requirement receiving a weight of 1;
- If the analyzed requirement is deemed equally important as the compared requirement, both receive weights of 2.

Subsequently, the weights assigned to each requirement are summated. Normalization procedures are then applied to ensure that these weights maintain proportionality, with an upper limit of 10. The outcome of this meticulous process yields the weighting factors that are to be incorporated into the subsequent evaluation matrix. As an illustrative example, a sample weighting matrix is provided in Figure 4.

	Requirement 1	Requirement 2	Requirement 3	Requirement 4	Sum	Weighting
Requirement 1	-	3	4	2	9	100%
Requirement 2	1	-	3	2	5	56%
Requirement 3	0	2	-	3	5	56%
Requirement 4	2	2	1	-	5	56%

Figure 4: Example of weighting matrix.

Next, a structured evaluation matrix should be established. This matrix comprises a defined set of criteria, a ranking scheme (typically numerical), and the individual relevance or weight assigned to each criterion. This framework sets the stage for an objective assessment. Experts from various disciplines should participate in the evaluation process, drawing upon their experience to fill out the evaluation matrix for each concept. This diverse perspective ensures a holistic view.

Once the matrix is completed, an overall ranking can be calculated using weighting factors (g_i) and a fulfilment value (n_i) of the variant against the specific requirements. This step aggregates the individual criterion rankings into a composite score for each concept. As an illustrative example, a sample evaluation matrix is provided in Table 1 for reference, using a fulfilment value between 0 and 4.

	Weighting	Variant A		Variant B		Variant C		max(n_i)	$g_i \times \max(n_i)$
	g_i	n_i	$g_i \times n_i$	n_i	$g_i \times n_i$	n_i	$g_i \times n_i$		
Requirement 1	10	3	30	4	40	2	20	4	40
Requirement 2	5.6	2	11.2	4	22.4	3	16.8	4	22.4
Requirement 3	5.6	2	11.2	4	22.4	4	22.4	4	22.4
Requirement 4	5.6	4	22.4	1	5.6	2	11.2	4	22.4
Sum		74.8		90.4		70.4			107.2
QFD-value for requirement		69.78 %		84.33 %		65.67 %			100 %

Table 1: Example of evaluation matrix.

Finally, concepts with the highest overall rankings should be selected as top candidates. It is worth considering the inclusion of individual concepts, even if their rankings are comparatively low, if they hold specific value or unique characteristics that align with the project's goals. This inclusive approach ensures that all valuable options are considered in the decision-making process.

4. Phase 2: Plant design on load point level

Load point design is traditionally used in power plant and chemical engineering since plants usually run at full load. However, in applications involving intermittent renewables, it becomes necessary to consider fluctuations in energy inputs, e.g., solar radiation. As a result, time step simulations have been developed to accurately reflect the varying load conditions under which the plant and its subsystems operate.

Detailed load point simulations, based on an adequate process design, serve as the foundation for time step simulations and allow for making initial estimates of annual yields from steady-state load point results.

4.1. Step 2.1: Definition of concepts, optimization variables, and evaluation criteria

Before starting the technical design and investigation of the concepts, it is vital to explicitly list the different concepts to be investigated (unique naming, numbering, short description). This can be result of Phase 1 or it can be an input from project partners.

In order to limit the dimension of the optimization space (number of free variables to be varied) some of the variables should be explicitly fixed for the investigation, while others are considered as free variables. This step should be done very carefully with the help of experts since it defines the whole optimization process and, to some extent, even the meaningfulness of results. If the concepts to be investigated strongly differ in their setup it is essential to define a useful set of free variables together with appropriate evaluation criteria. Special attention is needed e.g., for the following scenarios:

- Concepts using different power sources, e.g., in one concept solar power is generated on site while the other uses fuels or electricity from the grid (whereas one source depends on the weather situation the other source might deliver independent 24/7);
- Solar power sources with different daily/seasonal characteristics are used – e.g., concentrated solar power (CSP), concentrated solar thermal (CST), photovoltaic (PV), direct process;
- Flexibility in the choice of the operating strategy (e.g., solar-driven strategy, 24/7 strategy with backup system). Certain operating strategies might be preferred by individual concepts.

Typical free variables are the solar field aperture area, storage system capacity, and size of heat transfer units, whereas often the capacity of the power station or chemical production unit is set to a suitable nominal value. For each of the free variables a reasonable range of tolerated/suitable

values shall be defined. Restrictions might result from technical feasibility or economic pre-knowledge on the concepts.

In addition to defining reasonable ranges for these free variables, it's crucial to consider the potential implications of setting restrictions. For instance, if we establish a minimum limit for the solar field area, we risk overlooking solutions that do not rely on a solar field but might emerge as the most cost-effective option in unique scenarios. By considering these consequences of restrictions, we can ensure a more flexible and inclusive approach to system optimization, one that allows for innovative and efficient solutions to flourish, even when they deviate from traditional norms.

4.2. Step 2.2: Component modelling

The technical concepts investigation conducted by DLR usually have a high degree of novelty either resulting from completely new components or from a new configuration of mature components. Analyzing the innovative component in a system context requires a component model that represents the essential functionality of this component in the overall system. Often, available models for the new component e.g., in finite element method (FEM) or computational fluid dynamics (CFD) are too detailed to be used in system modelling or are not yet coded in the system simulation software. Consequently, a modelling step might be required, considering the interface concept of the simulation model, the relevant operating modes for the component, and its basic functionality. Typical examples are mass and energy balances over the component. A suitable degree of detail is characterized by:

- The major impact of the model on the overall system is well reflected;
- Any more level of detail would increase the model itself without having a significant impact on the overall system.

To streamline the modeling process, it is recommended to start with existing models that feature similar basic elements instead of starting from scratch. This approach saves time and resources and ensures that the new model benefits from previous work on related components.

4.3. Step 2.3 & 2.4: Detailed design on load point level

Usually, the concepts to be investigated are composed of multiple sub-systems that interact with each other. In our applications, this can be the solar production (CSP, CST, PV), storage (thermal, electric, product), heat transfer, and (electro-)chemical reaction units. In a first step the heat and mass balance diagrams shall be created using plant design tools, like Aspen Plus* or EBSILON Professional†. The following description differentiates between the design of the process plant and the design of the solar-thermal units, since different software is typically used. Both units share

* Available at <https://www.aspentech.com/en/products/engineering/aspen-plus>.

† Available at <https://www.ebsilon.com>.

common interfaces that have to be clearly defined and provided with default/starting values before starting the designs. During the design of the process the values will usually be adapted.

4.3.1. Interface definitions and operation modes

Solar driven processes are transient processes by principle and consequently require transient models. In contrast, chemical fuel production processes typically are stationary operated due to their restricted flexibility. To generate first estimations for solar driven fuel production processes, simulations can be performed on selected load points (this can be achieved e.g., with the implementation of simplified storage systems).

For solar fuel production units, solar irradiation usually provides the thermal and/or electric power to run the chemical process. Typical interfaces between the solar and process plant are:

- Electricity from the solar plant for the chemical process plant;
- Heat provided by the solar plant for the process plant (supply and return temperatures and conditions need to be matched). In a simple configuration there is only one heat supply interface. In more complex setups there might be multiple of such interfaces;
- Irradiation provided by the solar plant for direct usage in the process plant.

The interface list has to include all interface variables (variables that are used by the design tools of the solar and the process plant), an agreement on the units to be used for the variables, and the type of variable (input or output for the two design tools). The design process is iterative and shall be done in two steps:

- Nominal load point for the solar and process plant;
- Part-load operation point for solar and process plant.

If storage and/or backup power is used in the concept, nominal and part-load operation of both plants do not have to coincide. Different operation modes can be the result, e.g., solar plant and process plant in operation during daytime, process plant powered by storage during night time, part-load operation of process plant during night time to avoid shut-down of units.

The operation mode list shall include all major operation modes that have to be considered. These operation modes serve as the basis for identifying load points for both the process and the solar plant. Establishing this operation mode list typically commences with a comprehensive examination of the plant. This analysis is conducted by scrutinizing the schematic diagram of the solar plant, which aids in comprehending the various ways the plant can function. Figure 5 illustrates a schematic diagram of a solar-hybrid gas turbine for reference.

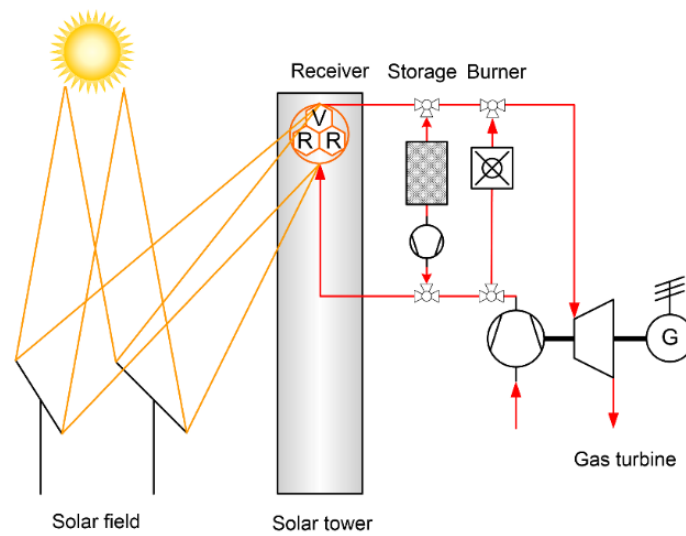


Figure 5: Schematic diagram - Solar-hybrid gas turbine.

With the schematic diagram and the design data at their disposal, practitioners can proceed to identify the different operation modes with the help of an auxiliary diagram. This diagram, for instance, could depict power versus time or production versus time. The primary objective of this diagram is to provide a clear representation of the various conditions that may arise during a certain period of time and how the plant should respond to these conditions.

For instance, in the power versus time of the solar-hybrid gas turbine diagram shown in Figure 6, it becomes evident that solar irradiation (red curve with parabolic shape) varies throughout the day, while the required power of the process remains constant (black horizontal line). As a result, seven distinct stages or conditions have been identified, each corresponding to a different point in the day.

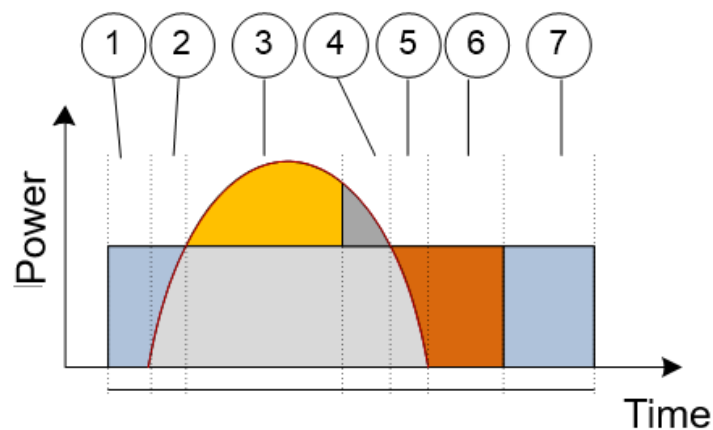


Figure 6: Power vs time diagram for Solar-hybrid gas turbine.

Now with the help of the auxiliary diagram, the operation mode list can be created as shown in Table 2.

Operation mode	Name	Description
1	Only-burner	- No solar radiation at receiver; - Thermal storage empty; - Entire compressor mass flow heated in the burner.
2	Warm-Up	- Insufficient solar radiation to reach turbine inlet temperature; - Rest mass flow is heated in the combustion chamber; - Receiver and combustion chamber mass flows are mixed and sent to the turbine.
3	Charge	- Solar power at receiver is enough to heat the compressor mass flow; - Excess receiver heat can be stored by recirculation.
4	Forced-defocus	- Thermal storage is full and cannot absorb more heat; - Heliostats are defocused to reduce solar input; - Entire compressor mass flow is directed through the receiver.
5	Cool-down	- Insufficient solar radiation to reach turbine inlet temperature; - Rest mass flow is heated in the storage (discharge); - Storage and receiver mass flows are mixed and sent to the turbine.
6	Discharge	- Entire compressor mass flow routed through the thermal storage before entering the turbine.
7	Only-burner	- No solar radiation at receiver; - Thermal storage empty; - Entire compressor mass flow heated in the burner.

Table 2: Operation mode list for solar-hybrid gas turbine.

4.3.2. Process plant design

The main purpose of creating flowsheet simulations is to investigate in detail the interdependencies between the main production steps within the fuel production route in terms of process parameters, energy efficiency and economic cost saving potentials. Energy and mass balances are drawn up for each sub-system and thus also for the entire process. Input and output flows of the chemical process can then be linked to other process parts, e.g., solar energy generation. Detailed steady-state process simulations should only be created for the most promising process concepts.

With the help of a process simulation software (e.g., Aspen Plus) the basic process operators of the required equipment can be mapped and linked in a meaningful way. Standard process equipment includes heat exchangers, compressors, pumps, turbines, columns or reactors. The operators required for calculating the different process steps and sub-systems can be modeled individually for the respective equipment. This includes chemical reactions, separation of mixtures, phase separations, changes in pressure, temperature or phase, mixing of flows, etc. Auxiliary equipment that does not have significant potential for heat and material integration is simply modeled as a black box with specific power and heat requirements. The interconnection of the required equipment

plays a crucial role in the process design. By iteratively adapting the interconnection of the process operators, the optimal constellation for the given problem can be determined.

For the final process constellation, a pinch-point analysis has to be performed to optimize the heat flow integration within the process and thus minimize utility costs for external heating or cooling. The design of the heat transfer network plays a critical role in optimizing the energy efficiency and operating cost of the chemical production facility.

With the preliminary process design in place, the equipment used can be designed techno-economically. This involves determining the size, capacity, flow rate, or other characteristic parameters of the equipment, which serve as the basis for the following economic evaluation.

The outcome of this step is to obtain a rough idea of the sizes of components and the initial layout of the plant. This provides a foundation for subsequent simulation and optimization efforts. The information gathered here serves as a crucial link to the next steps, where further fine-tuning and optimization of the fuel production process will be conducted to achieve enhanced efficiency, energy savings, and cost-effectiveness.

4.3.3. Solar plant design

The main goal of the solar field design is the efficient and useful integration of the solar resource into the fuel production process. A solar thermal power plant can provide both, heat and electricity, to run a fuel production process. With the help of suitable storage systems, continuous energy supply can be ensured.

4.3.4. Technical evaluation of system integration

The technical evaluation provides crucial information on the technical performance of the simulated process constellations. The performance indicators provide information about possible improvements and potentials of a process.

Technical performance indicators can be, e.g., overall process efficiency, product specifications and yield or conversion efficiencies. These parameters can be evaluated and compared for different operating conditions and modes in the first place to check relevant load points. For this, energy and mass flows of the most important streams have to be evaluated. On the basis of that a Sankey-analysis can be performed properly. The Sankey-analysis should include all relevant process steps to indicate e.g., energy and mass losses.

For solar fuel production pathways, a typical performance indicator is the solar-to-fuel efficiency (η_{stf}), shown in the equation below. It indicates how much of the available sunlight (Q_{solar}) can

be converted (and stored) into electricity (P_{el}), energy content of a fuel (Q_{fuel}) or a combination of both. It implicates the sum of all energy losses in the process, e.g., solar field losses, energy conversion losses or chemical conversion losses. Here it is important to specify whether the energy content of the fuel was determined based on the low heating value (LHV) or the high heating value (HHV).

$$\eta_{stf} = \frac{Q_{fuel} + P_{el}}{Q_{solar}}$$

4.4. Step 2.5: First estimate of annual yields and economics

By having access to the technical data from heat flow diagrams for different operation modes, it becomes possible to perform a first economic pre-evaluation. This is meaningful if the annual number of operating hours in the various operation modes can be estimated from the character of the concept which is typically the case for simple systems. However, when concepts involve significant seasonality or storage operations, these estimates become less precise. Nonetheless, they can still be useful for eliminating fewer promising concepts and thereby streamlining the subsequent detailed time series analysis.

The approach is in principle the same as in the detailed economic analyses (see Chapter 6) with the following simplifications:

- Technical production and consumption are estimated based on a number of typical operating points, each with an estimated annual operating duration (in hours). The challenge is to produce a good approximation of these operating durations;
- Cost assumptions might be less refined in this stage.

In addition to the economic evaluation of further technical aspects derived from the heat balance diagrams and the operation mode, analysis can already be included in the assessment:

- Technology availability (TRLs of the various subsystems);
- Process flexibility;
- Technical difficulties;
- Auxiliaries required;
- Environmental and safety hazards;
- Availability and cost of material/equipment;
- Storage requirements;
- Amount of land required;
- Maintenance and labor requirement;
- Possibility of future developments. Potential for improvement.

Although the pre-assessment can be helpful, especially when a large number of technical variants are still in the game, the evaluation should be done with care and complete exclusion of concepts should be well assessed.

5. Detailed yield analysis on time step level

Due to the variations of the main energy input from the sun, a detailed yield calculation for at least one typical year should be performed for the plant designed according to Chapter 4. The timestep used for this annual yield calculation should be of one hour or less, depending on the resolution of the available meteorological dataset but also on process requirements and design. Numerical considerations also may require a finer timestep.

Simulation of a typical year with hourly resolution should be considered as minimal requirement but eventually further simulations like multi-year or P50 and P90 yield calculations may be necessary. More details are given in Chapter 3 of the guideline by Hirsch (2017).

5.1. Step 3.1: Definition of site and market boundary conditions

Prior to the annual yield calculations, the boundary conditions must be defined and documented. Since solar applications are sensitive to the sun position and irradiation conditions on site these parameters are of great importance. The site coordinates (latitude and longitude) must be fixed as well as height above sea level.

In a next step a meteorological dataset with the chosen temporal resolution for this specific site must be acquired. There are several options for free dataset as well as commercial suppliers offering such datasets. For pre-feasibility and feasibility studies free datasets are the suitable choice. One resource for such datasets is the National Solar Resource Database (NSRDB)[†] and another one is the METEONORM software[§], which is capable to generate such datasets for almost all sites on earth (except for arctic regions).

Depending on the plant to be simulated the dataset must contain at least the following information for each time step: direct normal irradiation (DNI), global horizontal irradiation (GHI), diffuse horizontal irradiation (DHI), ambient temperature, ambient pressure, ambient humidity, and wind speed.

Special attention should be paid to the time zone of the meteorological dataset and its corresponding time stamp definition. Both of these aspects must be in sync with the definitions used within the simulation software. Meteorological datasets derived from satellite data often utilize Coordinated Universal Time (UTC) or Greenwich Mean Time (GMT) since satellites are not influenced by time zones. However, when analyzing load curves and other site-specific information, it is more practical to refer to the local time zone. Therefore, adjustments or conversions may be necessary

[†] Available at <https://nsrdb.nrel.gov>.

[§] Available at <https://meteonorm.com>.

to align the satellite-based meteorological datasets with the local time for accurate analysis and interpretation of the data.

It is noteworthy that meteorological datasets are often indicated with timestamps like "2-24 12:00" or similar. However, understanding the exact implications of this time stamp is vital. At least three distinct definitions come to light:

- i. The time stamp represents the start time of the interval;
- ii. It represents the center of the interval;
- iii. It represents the end of the interval.

The simulation model must use the same time stamp definition as the meteorological file since otherwise, there is a time shift between the datasets and the sun position calculation of the annual yield model.

The market boundary conditions must also be fixed and documented. This involves determining the prices for the generated products, electricity from the grid, and all necessary commodities. It is essential to consider whether these prices remain constant or vary over time. If the prices are time-dependent, it is necessary to have a dataset with the same time resolution as the simulation software.

Defining the prices for the products generated is paramount. Additionally, outlining the electric load curve that outlines the desired plant output for each time step is essential. This load curve should be accompanied by information clarifying whether it *must* or *should* be fulfilled by the plant. Furthermore, it might be necessary to establish distinct load curves for different plant sections. For instance, certain components may necessitate operating at a minimum load and should not be entirely shut down, as elaborated in Section 5.4.

In certain cases, a specific load curve must be defined in tandem with meteorological data. Our annual yield calculation models are typically steady-state or quasi-steady state models, but it's important to recognize that the radiation and heat input aren't consistently steady state. It's worth noting that these calculations do not encompass dynamic simulations. Therefore, at a minimum, some transient effects should be incorporated into the model, including:

- Start-up and shut down of the solar field and particularly the receiver;
- Start-up and shut down of the chemical plant.

These start-up procedures need energy and time which cannot be used for production but must be provided by solar energy or other sources. In contrast, when it comes to cooling down the system, it is important to note that the receiver and other components retain elevated temperatures even after several hours. As a result, restarting the plant after several hours or in the next morning may only require a fraction of the energy that would be needed initially for cold start up.

5.2. Step 3.2: Thermal storage units

CSP and CST plants are typically equipped with a thermal storage in order to allow for operation during night and low irradiation times. The two-tank molten salt storage system may be considered as state-of-the-art for these plants. Other storage systems are possible, e.g., molten salt thermo-cline, particle storage, etc. They can also be used for solar chemical plants if the reactor is heated indirectly.

5.3. Step 3.2: Chemical storage units

For solar chemical systems, storage tanks for intermediate and end products are needed. Their size could be optimized in order to fulfill the load curve or any production goal. Storage tanks for products at ambient temperature and ambient pressure offer the least cost option. This optimization could either be done by parameter variation or by using an appropriate algorithm considering specific costs of the different storage systems.

5.4. Step 3.2: Operation strategies

Operating strategies (OS) define which unit of the plant is operated at which load during a certain time step. Often this is not defined explicitly but rather implicitly depending on external or internal conditions. The operating strategy is associated with the load curve and must be defined in a way that the load curve could be fulfilled as good as possible. In the OS is also defined whether certain parts of the plant must be operated between certain load limits. Eventually different variants of OS must be considered in order to evaluate the one which fits best to the requirements. Operating strategies should be defined in the following steps:

1. Verbal description of the OS;
2. Definition of operating states;
3. Drawing of a flow chart including rules for individual paths;
4. Implementation in the annual yield software.

5.5. Step 3.3: Description of yield calculation approach

The simplest yield calculation model would be one with constant efficiencies for all subcomponents of the plant but as described above in this chapter, this would not be appropriate for solar applications. On the other hand, a full Aspen Plus or EBSILON Professional model of the whole plant would be difficult to handle and it is often very hard to implement detailed operating strategies and transient effects into those commercial simulation software tools. They were originally made for the simulation of single operating points rather than for time series. Although today, the time series simulation mode has been introduced in those tools, it needs long computation times for a full year

and often convergence problems occur when parts of the plant are in idle mode or when the plant is switching between operation modes.

Therefore, we often use a combination of self-developed software tools and the above-mentioned commercial tools. They offer interfaces to programming languages and may be called by other programs. Another option is to generate lookup tables for subsystems from Aspen Plus or EBSILON Professional and use them in the annual calculation software since this is much faster than calling them during each time step (eventually several times per time step if iteration for the whole system is required). The lookup tables must contain all input parameters which have a considerable impact on the subsystem performance (e.g.: load, input mass flow rate, temperature, pressure, etc.)

If an individual subsystem has an almost constant efficiency, it is of course sufficient to use this constant value, but unfortunately this case is very seldom for our applications. The next step of complexity would be a performance curve which solely depends on load.

5.6. Step 3.3: Yield calculation and technical evaluation

The primary outcome of the annual yield calculation is the total yield of the final product, which is indeed crucial. Nonetheless, depending solely on this yield value may prove inadequate and challenging to replicate without supplementary data. Therefore, it should be supplemented by an Excel or comma separated values (CSV) file containing hourly input values as well as intermediate results like:

- DNI, GHI, ambient temperature;
- Auxiliary consumption, consumption of commodities;
- Solar heat produced, storage charging and discharging flows, storage state-of-charge, curtailed heat;
- Electricity production, electricity self-consumption, electricity fed to the grid.

This list is not exhaustive but must be completed by other results depending on the application. The Excel or CSV-result file may be used to generate aggregated results like monthly, weekly, and daily values, which are eventually interesting in order to analyze the seasonal dependency of the production. The complete data book should also be stored together with the result files since it serves as documentation of the whole study.

The hourly results should be crosschecked prior to publication or release to the customer. This is not an easy task but the experience shows that there are several points which could give hints whether the results are trustworthy or not:

- Is the annual yield lower than the yield which could be calculated simply from the operating hours and the nominal efficiencies?

- Are the limits of subsystems (e.g., minimal and maximal output) observed in every single time step?
- Is the load curve satisfied or are there hours where it is exceeded or others where it is not fulfilled though there would be solar energy available or curtailment?
- Are the storage systems and tanks charged beyond their maximum content or discharged below zero?
- Is there any curtailment of energy generation even though there are available storage systems or grid capacity to accommodate the excess energy?

It is important to highlight that this list is not exhaustive, and should be adapted to the specific use-case.

6. Economic evaluation

Any techno-economic evaluation consists of the technical part (produced amounts, consumed amounts of energy and materials) and the economic evaluation. In the economic evaluation the CAPEX and the OPEX are compiled and used in an economic model which reduces the complexity to one or a few economic indicators referring to the amount of product generated. The following sections describe approaches for this important part of TEA.

6.1. Economic models

In the literature, there are various approaches to economic process evaluation. The specific method used may vary from case to case, depending on the particular context and requirements. To ensure the comparability of the results, it is essential to apply a uniform methodology. In principle we can distinguish between levelized cost of production models and profitability models based on balancing cash flows, as summarized in Table 3 and described in the following sections. For our typical applications both models are in principle usable. Once multiple co-products are generated the profitability approach will lead to a more consistent and transparent calculation since weighting factors for the levelized cost approach are difficult to define.

	Levelized cost of production (e.g., LCOE, LCOH, LCOH₂)	Profitability models (e.g., NPV)
<i>General idea</i>	Relate costs of production (CAPEX and OPEX) to the produced amount of product.	Summarize all costs and related financial incomes.
<i>Unit</i>	Financial unit per production unit (e.g., €/kWh _e , €/kWh _{th} , €/kg of H ₂).	Financial unit (e.g., €).
<i>Preferred application</i>	Comparison of concepts with one single product (e.g., electricity, heat, H ₂).	Comparison of concepts with multiple products (e.g., H ₂ + electricity, or electricity + heat). Financial evaluation of a project (investment decision).
<i>Required input parameters</i>	CAPEX and OPEX cost values; Real interest rate (e.g., 5 %); Annual production; Project lifetime (e.g., 20 years); Interest rate (e.g., 8 %); [value after life time].	Additionally: selling price of products.
<i>Benefits</i>	Easy to use; Commonly applied; Only a few assumptions needed (transparency).	Individual distribution of costs and production over life time can be represented. Considers profits and allows direct comparison to company internal benchmarks. Can be used for multiple co-products.
<i>Drawbacks</i>	Does not consider profits; Application to multiple products requires complex weighting factors.	Period individual calculation needs more effort and further assumptions; Comparing different sites or constellations is difficult since the metrics are not normalized.

Table 3: Overview on economic models.

6.1.1. Cost/income balancing models (e.g., NPV, IRR)

Important economic measures of a project include the net present value (NPV), internal rate of return (IRR) and payback periods – simple payback period (SPP) and discounted payback period (DPP) – which are essentially metrics to account for the balance of capital inputs and outputs during the project's lifetime. A project's NPV is a measure of its financial feasibility, accounting for both revenues and costs. It is defined as the overall cash flow discounted to year zero using the nominal interest rate, according to the following equation:

$$NPV = \sum_{t=0}^n \frac{C_t}{(1+i)^t}$$

where C_t is the unlevered free cash flow in year t , n is the analysis period (in years) and i the nominal interest rate. It is noteworthy that the real interest rate could also be used without any effect in the NPV obtained, however in this case the inflation rate must also be applied to the cash flows, which generally increases the complexity of the calculations.

In general, for a given interest rate, a positive NPV indicates a profitable project, an NPV of zero indicates a project that breaks even and a negative NPV indicates a project that costs more than it earn in revenue. Among the strategies for increasing the NPV are: reduce installation and operating costs, increase incentives, increase the interest rate, increase revenue (e.g., decrease IRR target), and in the case of projects involving power purchase agreement (PPA), increasing price, or increase savings (adjust retail electricity rate or load) for distributed projects.

When evaluating the financial feasibility of a project, it is advisable to check the NPV in combination with other metrics, such as the IRR, PPA price, and size of debt, to make sure they all lie within reasonable limits. For example, a positive NPV with an unrealistically high IRR may indicate that the project revenues are unrealistically high compared to the project costs. Similarly, a project that requires a high PPA price to achieve a positive NPV may not be competitive in a bidding process.

The IRR is the interest rate that, when applied to the project's cash flow brought to present, makes the outcomes equal to the incomes, i.e. indicates the interest the project generates on the overall capital during its lifetime is null. The IRR is calculated as the interest rate which results an NPV equals zero, using the following equation:

$$NPV = \sum_{t=0}^n \frac{C_t}{(1+IRR)^t} = 0$$

This metric reflects the fundamental economic viability and return of a project, disregarding financing mechanism and conditions, thus allowing a straightforward comparison of a wide variety of investment activities with a minimum acceptable rate of return (MARR).

Lastly, the payback period refers to the period it takes to recover the capital invested in a specific venture. There are two metrics for this calculation: the SPP and the DPP. The SPP accounts for the value of the system products (e.g., hydrogen and/or electricity), installation and operating costs, incentives, income taxes, and depreciation. On the other hand, the DPP also accounts for the time value of money by using cash flows discounted at a nominal interest rate. The SPP is suitable for evaluating the economic viability of a project when all cash flows are regular over years. Whereas the DPP provides a better representation for projects with the features such as debt, one-time or irregularly-timed costs (such as equipment replacements or other investments that occur in a specific year), and tax incentives that change over the lifetime of the project.

6.1.2. Production cost models, e.g., LCOE, LCOH₂

Levelized costs are effective indicators for evaluating the economic competitiveness of many processes, providing quantitative measurements of the economic feasibility of specific technologies. Key metrics include the LCOE, LCOH, LCOH₂, LCOF; for electricity, hydrogen, heat, and any other fuel, respectively. These indicators simplify the representation of the NPV, dividing it by the amount of electricity (kWh), heat (kWh), hydrogen or fuel (kg) produced, respectively. This relationship between NPV and LCOE is thoroughly detailed by Short et al. (1995).

The LCOE, for example, represents the average cost of generating electricity over the lifetime of a power plant, incorporating expenses such as financing, construction, fuel, operation, and maintenance. Alternatively, it can be interpreted as the average selling price of the produced electricity that would ensure the project breaks even at the end of its operational lifetime. In such cases, the project's NPV becomes zero, and the IRR equals the interest rate. There are multiple methodologies for calculating the LCOE, but two approaches distinguish themselves, each tailored to different analysis depths. The first approach is a comprehensive and detailed method, while the second is a simplified version. These methodologies are commonly employed by various institutions, with the detailed method often attributed to the International Energy Agency (IEA) and the simplified version to the National Renewable Energy Laboratory (NREL).

The detailed method as defined in IEA (2020), includes a broad cash flow analysis, considering the specific cash flows associated with the project over its lifetime, including not only annual investment costs but also annual operating expenses, revenues from electricity sales, and salvages at the end of the project's lifetime. The NPV of these cash flows is then calculated, using an interest rate, as presented in the following equation:

$$LCOE = \frac{\sum_{t=1}^n \frac{C_t + C_{O\&M,t}}{(1+i)^t}}{\sum_{t=1}^n \frac{Q_{e,t}}{(1+i)^t}} = \frac{TLCC}{\sum_{t=1}^n \frac{Q_{e,t}}{(1+i)^t}}$$

The advantage of this approach lies in its ability to account for differing annual cash flows and electricity outputs, making it suitable for situations that demand more detailed analysis. The present value of all these cash flows over the lifetime of the project is called total life cycle cost (TLCC) and are equal to the numerator in the LCOE equation (Short et al., 1995). Table 4 summarizes the variables used to calculate the LCOE following the detailed method.

Variable	Description	Reference unit
C_t	Capital cost in year t	€
$C_{O\&M,t}$	Fixed and variable operation and maintenance cost in year t	€
i	Interest rate	-
$LCOE$	Levelized cost of electricity	€/kWh _e
n	Project's lifetime	a
$Q_{e,t}$	Electricity produced in year t	kWh _e
t	Year t of project's lifetime	-
$TLCC$	Total life cycle cost	€

Table 4: Description of variables for calculating the LCOE using the detailed method.

In contrast, the simplified version of the levelized cost of energy (sLCOE), as stated in NREL (2010), is calculated in terms of the annual cost of energy, where the capital costs include an annuity-based capital recovery factor (CRF), which addresses the costs of financing the capital for the project, given as follows:

$$sLCOE = \frac{c_0 \cdot CRF + c_{O\&M,fix}}{8760 \cdot CF} + c_{O\&M,var}$$

$$CRF = \frac{i \cdot (1 + i)^n}{(1 + i)^n - 1}$$

Table 5 summarizes the variables used to calculate the sLCOE.

Variable	Description	Reference unit
c_0	Overnight capital cost	€/kW _e
$c_{O\&M,fix}$	Fixed operation and maintenance cost	€/(kW _e a)
$c_{O\&M,var}$	Variable operation and maintenance cost	€/(kW _e a)
CF	Capacity factor	-
CRF	Capital recovery factor	-
i	Interest rate	-
n	Project's lifetime	a
$sLCOE$	Simplified levelized cost of electricity	€/kW _e

Table 5: Description of variables for calculating the LCOE using the simplified method.

Under this approach, the entire capital investment is captured by the overnight cost of capital variable, while subsequent cash flows are assumed to remain constant throughout the project's lifetime. In addition, the electricity production is calculated as the average annual capacity factor (CF), making this method suitable for less comprehensive analyses. Particularly, it proves valuable in situations where limited data is available.

It is important to highlight that simplified method is derived from the detailed one, so under certain simplifying assumptions, both methods for calculating the LCOE produce the same output, as explored by Aldersey-Williams and Rubert (2019). These simplifying assumptions are: the project has constant annual output and costs, all construction spending occurs in year 1, capital recovery starts immediately with a financing term equal to the project's operating lifetime and that there are no decommissioning costs.

Similar to the LCOE, the LCOH and the LCOH₂ are effective indicators for measuring the economics of heat supply and hydrogen production, respectively. These metrics represents the average selling price over the project's lifetime (e.g., euros per kilowatt-hour of heat or kilogram of hydrogen), which equals the sum of the expenditures of this operation.

6.1.3. Cogeneration cost model

In cogeneration facilities, where multiple products are produced (e.g., heat, electricity, and/or chemicals), an equipment could be employed in the generation of more than one product stream. Thus, to avoid overlapping individual product costs, a criterion should be followed, such as in the following equations:

$$TLCC = \sum_{p=1}^n TLCC_p = TLCC(w_1 + \dots + w_p + \dots + w_n)$$

Table 6 summarizes the variables used in the previous equation.

Currently, there is no consensus about a method to be followed, yet Chiu and DeCoster (1966) provide a feasible solution for this. Based on the definition of specific product weights, shares of the TLCC can be allocated to each product. These weights are estimated based on physical properties or ability to generate income. In the first approach, the weightage can be allocated using the physical attributes of each product. Numerous physical factors are suggested, including mass, volume, production run time, energy or exergy content. On the other hand, in the weightage by the ability to carry costs, the weight of each product is obtained based on their ability to generate revenue streams. It can be considered not primarily as a way of allocating the weights among products, but as a way of allocating the profits. This method allocates the costs to each product in such a manner to assign the same percentage of gross profit to each product.

Variable	Description	Reference unit
n	Total number of products	-
p	Product p	-
$TLCC$	Total life cycle cost	€
$TLCC_p$	Total life cycle cost of product p ($TLCC_p = TLCC \cdot w_p$)	€
w_p	Weight of product p ($\sum_{p=1}^n w_p = 1$)	-

Table 6: Description of variables for calculating the TLCC in cogeneration.

Alternatively, when the cost of one of the by-products is known, for example in combined heat and power (CHP) plants subject to a fixed electricity trading price, a common practice is to allocate the costs so this product achieve break even, while the remainder is allocated to the other products, in this case heat.

6.2. Categories of capital cost estimation

An estimate of the capital investment for a process may vary, for example, from a simple predesign estimate based on internal information from past or recent projects, to a detailed estimate prepared from complete engineering specifications and market quotations. Between these two extremes, there can be numerous other calculations varying in accuracy, which as a general rule, increases with the level of information available. Peters et al. (2003) divide them in five levels, receiving the nomenclature shown in Table 7.

According to this classification, an order-of-magnitude estimate is achieved when rough assumptions regarding the final product, site requirements, project capacity and location are considered, resulting in a difference between actual and estimated project costs often exceeding 30 %. On the other hand, a detailed estimate, with typical accuracies around 5 %, should encompass the engineered specifications of all relevant elements of the project, such as equipment, utilities, piping, instrumentation and labor. The types of information required by each of these five levels of estimates can be found in the work by Peters et al. (2003).

Title of estimate	Definition	Approximate accuracy
<i>Order-of-magnitude</i>	Estimate based on similar previous cost data.	Over ± 30 %
<i>Study or factored</i>	Estimate based on knowledge of main pieces of equipment.	± 30 %
<i>Preliminary</i>	Estimate based on sufficient data to permit the estimate to be budgeted.	± 20 %
<i>Definitive</i>	Definitive estimate based on almost complete data, but before completion of system specifications.	± 10 %
<i>Detailed</i>	Detailed estimate based on complete engineering specifications, and site surveys.	± 5 %

Table 7: Definition and typical accuracy of cost-estimating types according to the level of information.

Much of the information needed to perform these estimates can be found in the literature. Notable examples of works containing cost involved in plant design are the books by Ulrich and Vasudevan (2004), Towler and Sinnott (2022), and Turton (2018).

Predesign cost estimates, which encompasses the first three levels in Table 7, require much less data than firm estimates such as in the last two levels. Nevertheless, predesign estimates are extremely important for determining whether a process proposal should be given further consideration and may be used for requesting and obtaining funding from company management. Later and more comprehensive estimates, made during the progress of the design, may indicate that the project will cost more or less than the first anticipated and be used to justify budget adjustments.

6.3. Estimation of capital investment

To estimate the capital cost of a fuel production plant, it is essential to dimension the utilized equipment in the first place. The costs for purchasing this equipment are the base for further estimations of direct and indirect costs concerning the overall plant.

Estimating the capital investment for a plant is a critical step in the project's planning and financial analysis. Properly dimensioning the utilized equipment provides the foundation for further estimations of direct and indirect costs related to the overall plant. In this regard, we have compiled a comprehensive CAPEX cost structure table, which encompasses engineering, procurement, and construction (EPC) costs, owner costs, and financing costs. Table 8 will serve as a valuable reference

to gain insights into the distribution of capital expenses and aid us in making informed decisions as we progress with the project.

Understanding the components of the cost structure and precisely defining what each value includes is of paramount importance when estimating the CAPEX of a plant. The definition of each system cost can vary significantly, as sometimes the price of a component may include the entire system's cost, while in other cases, it may pertain to only a single element of the system. Such discrepancies can lead to confusion and inconsistencies in the overall cost estimation.

Item	Reference/description	Reference unit
<i>EPC Costs</i>	Sum of EPC direct and additional costs	€
<i>EPC direct costs</i>	Sum of following items	€
<i>Site Preparation</i>	Total land area	€/m ² _{land}
<i>System/component 1</i>	Based of reference value (power, area, etc.)	€/m ²
<i>System/component 2</i>	Based of reference value (power, area, etc.)	€/kWh _e
<i>System/component N</i>	Based of reference value (power, area, etc.)	€/kWh _{th}
<i>EPC indirect costs</i>	Sum of following items	€
<i>Engineering, management and other EPC services</i>	Fraction of EPC direct costs	%
<i>Profit margin and contingencies</i>	Fraction of EPC direct costs	%
<i>Owner's costs</i>	Sum of following items	€
<i>Project development</i>	In percentage of total EPC cost	%
<i>Land cost</i>	Land lease (if applicable)	€
<i>Utility connections</i>	(If applicable)	€
<i>Additional owner's costs</i>	In percentage of total EPC cost	%
<i>Total overnight cost</i>	Sum of EPC Cost and Owner's costs	€
<i>Financing costs</i>	Financing costs	€
<i>CAPEX</i>	Sum of total overnight cost and financing costs	€

Table 8: Template for CAPEX breakdown table.

To ensure accuracy and consistency in our analysis of typical systems at the DLR, it is imperative to rely on reliable information gathered in the cost databases. By such resource, we can achieve a standardized approach to cost evaluation and mitigate potential misunderstandings or disparities in our assessments.

6.3.1. Scaling, inflation and projection methodology

When cost data is not available for a component or subsystem capacity, upscaling or downscaling calculations can be made using the power relationship if the target equipment resembles a

reference one with available costs. According to this rule, if the equipment cost in reference year (C_1) with size or capacity S_1 is known, the cost of a similar unit in the same year (C_2) with a target capacity S_2 is given by the following equation, where sf is the scaling factor.

$$C_2 = C_1 \cdot \left(\frac{S_2}{S_1}\right)^{sf}$$

Scaling factors for different chemical process and equipment sizes are provided by Peters et al. (2003) and Ulrich and Vasudevan (2004). Here, the common six-tenths factor rule, where the scaling factor of 0.6, is often used. However, applying this to most purchased equipment is an oversimplification, as actual cost capacity exponents vary in a wide range (usually from less than 0.3 to greater than 1). Thus, the 0.6 exponent should be used only when no other information is available, primarily for rough feasibility estimates within a ten-fold capacity range. Equipment characteristics like technology, construction, materials, and operating ranges must be similar for valid application.

In addition to that, cost data for preliminary estimates becomes outdated due to economic changes over time, so alongside scaling, a method is needed to calculate $C_{2,y}$, the updated past cost data to present conditions. This involves multiplying known equipment cost in reference year r ($C_{1,r}$) by the ratio of cost index in the desired year y (I_y) to cost index in reference year r (I_r) as shown in the following equation.

$$C_{2,y} = C_{1,r} \cdot \left(\frac{I_y}{I_r}\right) = C_{1,r} \cdot \left(\frac{S_2}{S_1}\right)^{sf} \cdot \left(\frac{I_y}{I_r}\right)$$

Cost indexes show costs relative to a base time, helping estimate equivalent present costs. While useful for general estimates within a ten-year range, indexes may not account for all factors like technology or local conditions. Different types of cost indexes are published regularly, e.g., for equipment costs and others for labor, construction, materials, or specialized fields. These indexes, based on limited sampling, may vary considerably. The Chemical Engineering Plant Cost Index (CEPCI) is usually recommended for estimating process equipment and chemical-plant investment costs. According to Short et al. (1995) and Ulrich and Vasudevan, this methodology can also be used to extrapolate costs into the near future, calculating the cost indexes based on projected inflation rates. Nevertheless, the analysts should acknowledge the uncertainty of projected inflation rates and consider performing sensitivity analysis with a range of inflation rates.

Another important aspect to consider when projecting the future costs of different components is the learning curve. As a technology becomes more widely deployed, processes like design, manufacturing, installation and operation tend to improve and standardize, leading to cost reductions. The experience curve approach facilitates cost projections using historical cumulative development, anticipated growth, and technology-specific learning rates. Thus, the projected technology-specific cost for a predicted installed capacity can be calculated using the following equation:

$$C_2 = C_1 \cdot \left(\frac{P_2}{P_1}\right)^{\frac{\log(\text{progress ratio})}{\log 2}} = C_1 \cdot \left(\frac{P_2}{P_1}\right)^{\frac{\log(1-\text{learning rate})}{\log 2}}$$

where C_2 represents the technology-specific cost at the predicted cumulative installed capacity P_2 , while C_1 is the cost at the initial cumulative installed capacity P_1 . The progress ratio is defined as one minus the learning rate, indicating the proportion of the initial cost when the cumulative installed capacity doubles. This methodology is explored further in Neij (2008) and Breyer et al. (2017), which estimate learning rates for various renewable energy technologies, including CSP.

A significant portion of the uncertainty associated with such calculations is linked to assessing future cumulative installed capacity, which often varies greatly among different sources. An advisable approach involves considering multiple assessments to provide a cost estimate range based on pessimistic and optimistic outlooks, rather than a single value, as performed by Breyer et al. (2017). The experience curve approach is also employed by NREL in the Annual Technology Baseline (ATB), a annually released database projecting the CAPEX, OPEX, and LCOE of renewables until 2050 (NREL, 2023).

In an alternative approach, as detailed in the study by Dersch et al. (2020), a method has been employed to provide insights into the future cost dynamics of components in CSP/CST systems. This method is distinctive in that it amalgamates the perspectives derived from technological advancements and the expertise of specialists within the CSP sector.

Essentially, as new technologies and advancements emerge, it is anticipated that they will play a pivotal role in driving down the costs associated with components. This method fosters collaboration with specialists within the sector. These specialists bring to the table a wealth of knowledge concerning current industry trends, as well as insights into emerging technologies within the field. Their inputs, therefore, serve as a vital component in shaping the cost estimation process.

The strength of this approach lies in its ability to harness the collective expertise and domain-specific knowledge of industry professionals. Moreover, it is worth noting that this method may also encompass scenario analysis. This involves the exploration of various potential trajectories of technological progress and their corresponding impacts on the costs of components. This scenario analysis adds a layer of robustness to the estimations, allowing for a more comprehensive understanding of the potential future outcomes.

However, one notable weakness of this method is its dependence on finding and engaging experts in the specific sector under analysis. In sectors with limited pools of experts or in emerging industries where expertise is still evolving, it may prove challenging to assemble a panel of qualified specialists. Additionally, the method's outcomes may be influenced by the expertise and perspectives of the selected experts, potentially introducing bias or limitations in the estimation process.

6.3.2. Costs of chemical plant

Total cost of chemical plant can be estimated by calculating two major types of cost: Direct cost of equipment and indirect cost of equipment. In addition to these, few other costs like working capital and constants need to be considered to estimate the total capital investment required for the chemical plant.

Direct cost includes the costs for the purchased equipment, equipment installation, instrumentation and controls, piping, electrical systems, buildings, yard improvements, service facilities and land (Peters et al., 2003). For the calculation of standard equipment purchased cost, the equations provided for different equipment type in the chemical engineering books (see Section 5.2) can be referred. Besides equipment type, various other factors like material, pressure factor needs to be considered to generate equipment cost more precisely. In order to estimate direct cost based on the purchased equipment cost, Lang factor or ratio factors can be used. Lang factor helps in calculating the overall direct costs simply as a result of product with purchased equipment cost. However, the percentage of equipment cost method helps in performing detailed calculation of various costs like piping, electrical systems, etc. Table 11 can be referred to obtain the accurate Lang factors for a specific chemical process.

Indirect costs majorly consist of expenses for engineering and supervision, legal expenses, construction expenses, contractor's fee and contingency. These sub-costs can be easily calculated using the percentage of purchased equipment method. Using the equation below of purchased equipment cost method, and Table 9 and Table 10, direct and indirect cost can be estimated. In the equation, E stands for the cost of purchased equipment, and f denotes the cost factors for different costs. Depending on the type of process, the cost factor values can be chosen. Here Table 9 can be proven useful.

$$C_n = E \Sigma(1 + f_1 + f_2 + \dots + f_n)$$

Item	Fraction of purchased- equipment costs*	Min	Max	Fraction of FCI	Min	Max
<i>Direct Costs (manufacturing fixed-capital investment)</i>						
<i>Purchased Equipment</i>	100 %			19.8 %	15 %	40 %
<i>Equipment installation</i>	47 %	25 %	55 %	9.3 %	6 %	14 %
<i>Instrumentation and controls</i>	36 %	8 %	50 %	7.1 %	2 %	12 %
<i>Piping</i>	68 %	16 %	68 %	13.5 %	4 %	17 %
<i>Electrical</i>	11 %	15 %	30 %	2.2 %	2 %	10 %
<i>Buildings</i>	18 %	5 %	45 %	3.6 %	2 %	18 %
<i>Yard improvements</i>	10 %	10 %	20 %	2 %	2 %	5 %
<i>Service facilities</i>	70 %	30 %	80 %	13.9 %	8 %	30 %
<i>Land</i>	–	4 %	8 %	–	1 %	2 %
<i>Sum direct costs</i>	342.0 %			71.4 %		
<i>Indirect costs</i>						
<i>Engineering and supervision</i>	33 %	~30 %		6.5 %	4 %	20 %
<i>Construction expenses</i>	41 %			8.1 %	4 %	17 %
<i>Legal expenses</i>	4 %			0.8 %	1 %	3 %
<i>Contractor's fee</i>	22 %			4.4 %	2 %	6 %
<i>Contingency</i>	44 %			8.7 %	5 %	15 %
<i>Sum indirect costs</i>	144 %			28.6 %		
<i>Fixed capital investment (FCI)</i>	486 %			100 %		
<i>WC (15 % of TCI)</i>	85.8 %			15 %	10 %	20 %
<i>Total capital investment (TCI)</i>	571.8 %			115 %		

Table 9: Range of percentages of various cost for percentage of equipment cost method
(Peters et al., 2003).

Item	Fraction of delivered equipment costs		
	Solid processing plant	Solid-fluid processing plant	Fluid processing plant
Direct Costs			
<i>Purchased Equipment delivered (including fabricated equipment, process machinery, pumps, and compressors)</i>	100 %	100 %	100 %
<i>Purchase equipment installation</i>	45 %	39 %	47 %
<i>Instrumentation and controls (Installed)</i>	18 %	26 %	37 %
<i>Piping (Installed)</i>	16 %	31 %	68 %
<i>Electrical (Installed)</i>	10 %	10 %	11 %
<i>Buildings (Including services)</i>	25 %	29 %	18 %
<i>Yard improvements</i>	15 %	12 %	10 %
<i>Service facilities (installed)</i>	40 %	55 %	70 %
<i>Sum direct costs</i>	269 %	302 %	360 %
Indirect costs			
<i>Engineering and supervision</i>	33 %	32 %	33 %
<i>Construction expenses</i>	39 %	34 %	41 %
<i>Legal expenses</i>	4 %	4 %	4 %
<i>Contractor's fee</i>	17 %	19 %	22 %
<i>Contingency</i>	35 %	37 %	44 %
<i>Sum indirect costs</i>	128 %	126 %	144 %
<i>Fixed capital investment (FCI)</i>	397 %	428 %	504 %
<i>Working capital (15 % of TCI)</i>	70 %	75 %	89 %
<i>Total capital investment (TCI)</i>	467 %	503 %	593 %

Table 10: Fraction of delivered equipment costs for different plant basis (Peters et al., 2003).

Type of plant	Lang factor for fixed capital investment	Lang factor for total capital investment
<i>Solid</i>	4.0	4.7
<i>Solid-fluid</i>	4.3	5.0
<i>Fluid</i>	5.0	6.0

Table 11: Lang factors for the estimation of FCI and TCI (Peters et al., 2003).

Moreover, in the case of unavailability of data for a certain piece of equipment with specific size, the scaling effect is addressed by using the power law, as already discussed.

Further, during the estimation of direct and indirect costs, cost indices like the CEPCI are also considered. This helps in aligning all the cost of various equipment from different years and helps in

considering the inflation effect on the investment. The total fixed capital cost is the aggregate of direct and indirect cost.

Working capital cost of chemical plant majorly consists of investment in raw materials and supplies carried in stock, finished products in stock and semi-finished products in the process of being manufactured, accounts receivable, as well as the cash kept on hand for monthly payment of operating expenses, such as salaries, wages, and raw material purchases, also accounts payable. It could be estimated considering 15 % of the total capital investment. The sum of working capital and fixed capital investment gives the total capital investment.

6.3.3. Costs of solar system

In general, costs of the solar systems can be estimated using the same methods as for the chemical systems. Due to the smaller number of existing plants, no handbooks with cost information for the required equipment are available. Instead, the costs may be taken from other publications (preferably reporting costs of real plants) completed by expert guesses.

This database contains direct specific costs for the major components of solar systems like parabolic trough field, heliostat field, power block, tower, receiver, etc. These specific costs are based on relevant quantities like e.g., aperture area for the solar field, thermal power for the receiver, and thermal capacity for the storage. The database file also contains information about the items which are included in the major components. Actual direct component costs for a project can be calculated by multiplying the given specific cost values by the relevant reference value. If the size of the component differs significantly from the reference size given in the cost database, the corresponding scaling law should be applied.

In addition to these direct equipment costs, indirect cost must be considered, which are typically defined as percentage of the direct costs. They may be divided into indirect EPC costs, accounting for engineering, management and other EPC services and for EPC profit and contingencies. Furthermore, owners' costs must be added, accounting for project development and other owners' costs. These owners' costs are typically given as percentage of the total EPC costs (sum of direct and indirect EPC costs). Finally, land costs and costs for grid connections are added to the owners cost, if these cost positions are relevant for the project.

$$C_t = (f_{EPC} + f_{own}) \sum_{i=1}^m c_i a_i + C_{land} + C_{grid}$$

Table 12 summarizes the variables used in the previous equation.

Variable	Description	Reference unit
f_{EPC}	Factor of EPC	-
f_{own}	Factor of ownership	-
C_{land}	Cost of land	€
C_{grid}	Cost of grid	€
C_t	Total cost	€

Table 12: Description of variables for calculating the total equipment costs.

Although many components of solar plants are traded internationally and are manufactured by a small number of suppliers, some parts and services can be bought in the country where the plant is going to be erected. This applies particularly for site preparation and assembly work for large installations. For these parts and services local costs may be considered, if available. Extending the methods described above, one has to estimate the local fraction of the totals parts and services and get a local price index for them. An example for this approach is given in Dersch et al. (2020).

The specific difficulties for this extension are the estimation of local fractions and the availability of a meaningful price index. For these reasons the calculation of costs for individual countries is used very rarely. Furthermore, the extension is only relevant for the comparison between different countries and not for the of different technologies at one site.

6.4. Operating costs calculations

Operating costs are the total of all costs of operating the plant, selling the products, recovering the capital investment and contributing to corporate functions such as management and research and development. It is generally divided into manufacturing (or production) costs and general expenses.

6.4.1. Operating costs of chemical equipment

Operating costs of chemical equipment encompass all expenses associated with the functioning of a process plant, including its physical equipment in addition to plant overhead costs, which refer to the ongoing expenses incurred by the enterprise that are not directly tied to the production of process. The operating costs are commonly divided into fixed and variable costs.

Fixed operating costs encompass expenses that remain relatively stable regardless of production rate. Expenditures for depreciation, property taxes, insurance, financing (loan interest), and rent fall under this category. While some of these charges, excluding depreciation, may fluctuate due to inflation, depreciation follows a schedule dictated by tax regulations and remains unaffected by inflation.

Variable operating costs represent recurrent expenses directly linked to the manufacturing process. This category includes expenditures on raw materials, labor, utilities, maintenance, operating supplies, laboratory materials, royalties, catalysts, and solvents. These costs primarily arise during plant operation, hence their classification as variable costs. It is important to highlight that certain costs include a variable and a fixed share. For instance, maintenance and repair expenses decrease with lower production levels, although some maintenance and repair work may still be necessary during plant shutdowns.

6.4.2. Costs of solar system

As for capital investment, there is no general difference in operation costs for solar and chemical systems. They can be divided into fixed and variable operation costs.

Fixed operation costs are insurance, land lease, operation and maintenance (O&M) personnel cost, and O&M equipment cost. A typical approach is to estimate fixed O&M costs as percentage of the total investment costs, eventually divided into insurance and other fixed O&M costs.

$$C_{O\&M,fix} = (f_{O\&M,fix} + f_{ins}) \cdot C_t$$

Variable O&M costs are for water, grid electricity, other consumables like nitrogen and heat transfer fluid and eventually fuel. Their annual consumption should be a result of the annual yield calculation and the total annual expenditures can be calculated just by multiplying the annual consumption and the relevant price per quantity. A more general approach is to use one specific value of O&M costs based on one unit of the solar fuel (e.g., in €/kg of H₂) and calculate the total variable O&M cost just by multiplying this the specific cost figure with the total annual amount of solar fuel produced.

$$C_{O\&M,var} = f_{O\&M,var} \cdot a_{product}$$

6.5. Detailed economic evaluation

For most solar fuel production systems, the economic evaluation can be implemented as post-processing and can be done after the time series based annual yield calculation. In a first step the subsystems must be dimensioned and the operation strategy must be fixed. The annual yield calculation must be implemented and executed for this fixed design and delivers the annual production of solar fuel for a typical year as result. This yield, together with the design parameters like solar field aperture area, receiver thermal power, tower height, etc. can be used as input for the economic model (LCOH or NPV calculation).

One typical task for this kind of evaluation, is to find the least cost configuration where the design parameters like solar field aperture area, tower height, receiver thermal design power, etc. are treated as unknowns. In this case, two general options are presented:

- Use a parameter variation with a kind of regular grid which varies these unknown design parameters systematically and pick the least cost configuration from the simulated variants.
- Implement an optimization scheme where the optimizer is capable to vary the design parameters automatically, rerun the annual yield calculation and the economic model and evaluate the result to find the optimal combination of design parameters. That means those which lead to the lowest LCOH or the highest NPV.

The systematic parameter variation is the option which is easier to implement since global optimization of mixed integer nonlinear problems, which we typically have for these systems, requires high computational effort and the determination of the global optimum is not guaranteed.

For the parameter variation, it is necessary to define the most important parameters as well as their upper and lower boundaries and an appropriate step width. The detailed design on load point basis delivers valuable hints and first guesses for the parameters but not necessarily the optimal combination for a typical year. Either a large number of yield calculations and economic post-processing for different parameter combinations must be performed or the person doing the TEA, observes the LCOE or NPV development and reduces the number of necessary model-runs by choosing promising parameter combinations and omitting those which will obviously lead to higher LCOE or lower NPV.

Figure 7 shows an example of the parameter variation for a parabolic trough solar power plant. The most important parameters here are solar field aperture and thermal storage capacity. This figure shows that there exists a combination of these parameters which delivers the lowest LCOE for a given power block size and operating strategy. It is obvious that the number of necessary runs grow rapidly with the number of free parameters, thus is essential to fix as many parameters as possible prior to the optimization process.

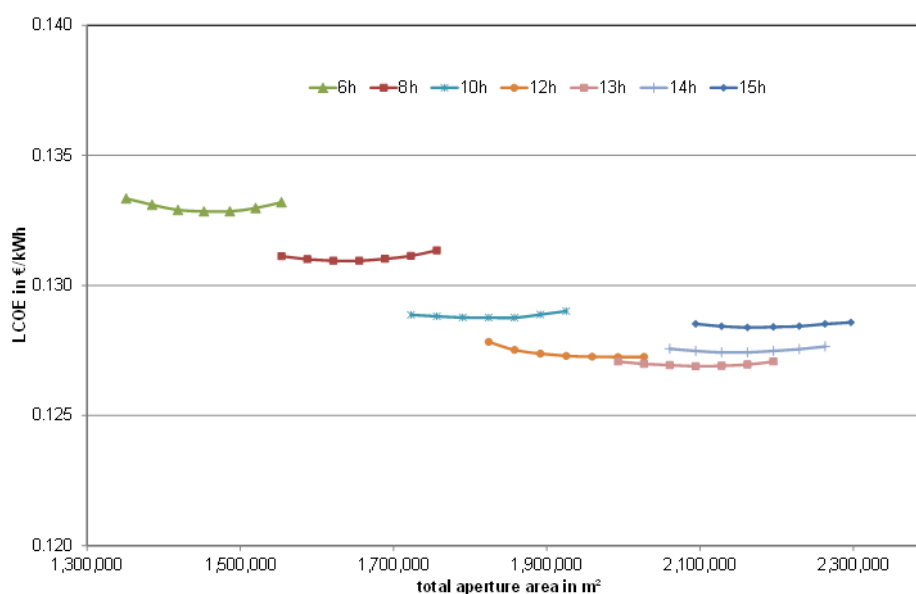


Figure 7: Result of a parameter variation for a parabolic trough solar thermal power plant. Parameters are: solar field aperture area and thermal storage capacity in full load hours of the power block.

The final report should contain one or several of these figures, as well as details about the optimal configuration found in the study. The complete data book describing all input parameters and boundary conditions is also an essential part of the final report. As the results are valid for a certain site, such information must also be included, together with some data characterizing the meteorological data at site.

Parameter	Value	Unit
Site longitude	37.83	°
Site latitude	-2.45	°
Annual cumulative DNI	1917.80	kWh/m²
Annual cumulative GHI	1812.42	kWh/m²
Annual mean ambient temperature	17.59	°C
Source of TMY data	Meteonorm	–

Table 13: Minimal site information for the TEA report. Example data for Almeria, Spain.

The assumed operation strategy for the plant must also be thoroughly described in the report since it might have a significant impact on the annual yield and the TEA results.

Sometimes, not only the optimum of a single value is required but the combination of two or even more results shall be combined and the optimum for the combination is wanted. One example

could be LCOE and carbon dioxide (CO₂) emissions for a hybrid plant using solar and fossil energy to produce fuels. Today, often the fossil energy is quite cheap and if one looks only for the lowest LCOE, this would lead to a system which is only fossil operated. On the other hand, this fossil only plant would have the highest CO₂ emissions. Such a combined optimization problem typically leads to a pareto front, showing several combinations of both parameters which fulfill the optimization requirements. All dark red points at the lower and leftmost border of the “result cloud” are representing optimal combinations or plants, which have the lowest LCOE for given maximum specific CO₂-emissions.

Since most cost assumptions are uncertain, a sensitivity analysis should be included in the report to demonstrate the impact of cost assumptions on the results. In principle, different cost assumptions can result in different parameter combinations for the optimal system. However, conducting a complete TEA multiple times to explore all possible configurations would require significant effort. Instead, a more efficient approach is to perform a sensitivity analysis on the configuration identified as optimal.

In this approach, the major cost input parameters are varied individually, and only the economic post-processing needs to be repeated. The outcome is a graphical representation that provides valuable insights into the impact of each varied cost input parameter on metrics such as the LCOE or NPV. This method allows for a clear understanding of the sensitivity of the optimal configuration to changes in cost assumptions.

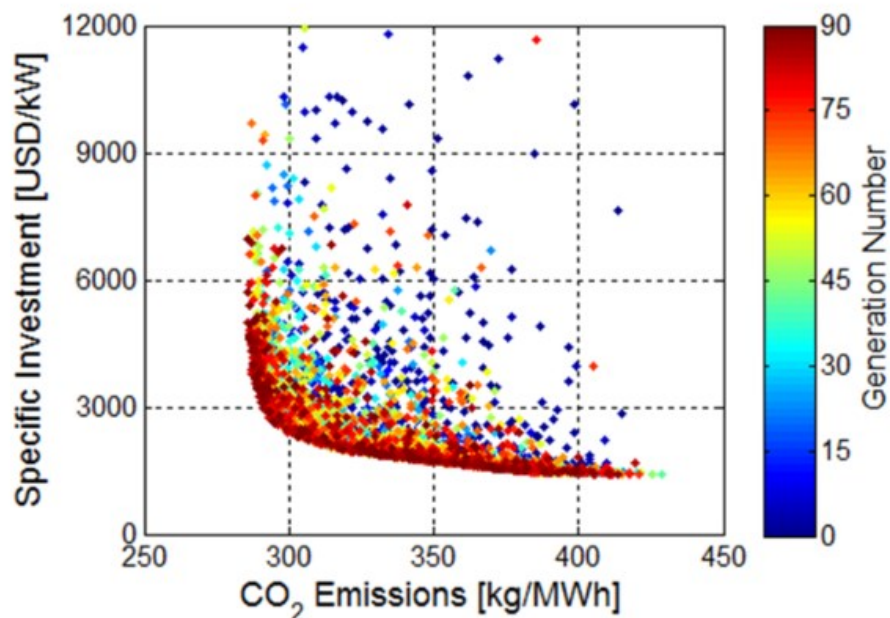


Figure 8: Pareto front generated during the optimization of a solar hybrid gas turbine system (Spelling, 2013).

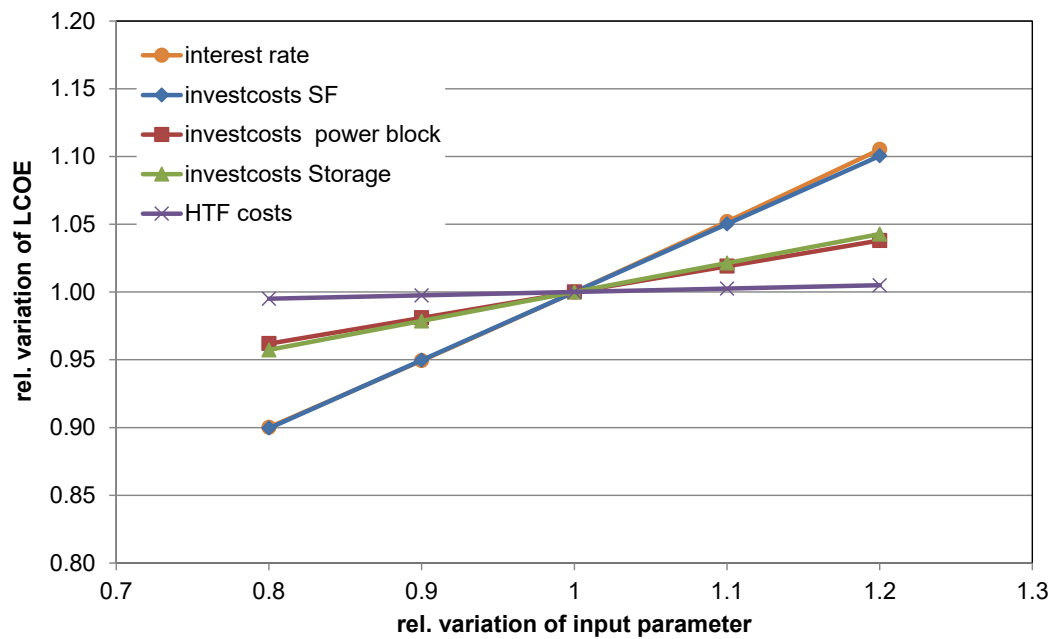


Figure 9: Example plot for a sensitivity analysis for cost assumptions using one technical configuration and varying each cost parameters individually.

7. Final comments

This guideline has been developed to provide a structured and transparent approach to the techno-economic assessment (TEA) of solar fuel production systems. By harmonizing internal practices and consolidating decades of experience, it aims to support consistent, comparable, and reproducible analyses across different projects and applications.

While the methodology presented here offers a solid foundation, it is important to recognize that TEA is not a static or universally prescriptive process. Each assessment depends on a specific technological context, boundary conditions, and objectives, which means that adaptation and critical judgment are essential. The recommended steps, models, and parameters should therefore be adjusted with care to reflect the reality of each case, ensuring that the results remain technically sound and meaningful.

Another key aspect to consider is the uncertainty inherent to early-stage technologies and innovative concepts. Both technical and economic assumptions often rely on limited data or projections, and these uncertainties should be explicitly documented and, whenever possible, explored through sensitivity analyses. Transparency regarding these limitations is fundamental for the credibility and interpretability of results.

Finally, this document should be regarded as a living guideline. Advances in modeling tools, cost estimation methods, and market frameworks will require updates to keep the recommendations relevant and aligned with best practices. Feedback from internal teams, project partners, and external stakeholders is therefore strongly encouraged to continuously improve this framework.

In summary, this guideline serves as a reference to promote consistency and quality in TEA studies, while leaving room for innovation and adaptation. Its ultimate value lies in supporting robust decision-making, facilitating knowledge transfer, and strengthening collaboration in the development of sustainable solar fuel technologies.

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