TEA of cultivated meat

Future projections of different scenarios - corrigendum

CE Delft

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This report was prepared by:
Robert Vergeer, Pelle Sinke, Ingrid Odegard

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Further information on this study can be obtained from the contact person Pelle Sinke or Robert Vergeer

Content

Explanatory note with the corrigendum

In February 2021, we have published the TEA and LCA for cultivated meat. In the TEA, we develop a model for the Cost of Goods Sold (COGS) for cultivated meat, based on current production technology and costs for inputs. Then, we explore various scenarios for cutting costs when production takes place in full-scale plants, realised in 2030. In this corrigendum, we correct two errors in our analysis and we provide an additional clarification:

Removal of Scenario 7 (higher cell density)

In Scenario 7 of the original TEA, we explore the impact of running the production process with a higher cell density. Then, in Scenario 9, we combine a higher cell density with a larger cell volume. We have discovered that combining a higher cell density with larger cell volume is physically impossible adopting the quantitative assumptions in our model.

In this corrigendum, we remove the scenario with higher cell density (original Scenario 7) from the study. The scenario where we explore the effect of higher cell volume is no longer combined with a higher cell density.
This has an impact on various figures in the report and the exact values of $/kg CM for the scenarios mentioned. We publish the new values in the report.

New price for hydrolysate

The source used for determining the lower end of the price of soy hydrolysate (Appendix B.2) is for agricultural grade hydrolysate. This is not in line with our assumptions of food grade process inputs. When a price of food grade soy hydrolysate is used (as pursued by CM-producing companies), the total costs per kg CM in the low-medium scenarios (3-8) increase by $ 0,29. This is smaller than 10% of total costs in the low, mid and high-medium scenarios. We have updated the COGs figures based on the new price.

Clarification

We have added some clarification on what we understand the ‘food grade’ hygiene standard for the production process to be, and why we adopt this standard. This standard is (and was originally) reflected in the investment cost estimate and energy requirements.

Neither both corrections, nor the clarification, alter the qualitative conclusions in the report.

Summary

In this report[1], we make a Techno-Economic Analysis for the production of cultivated meat (CM) at industrial scale, in the 2030's. We first develop a model for the Cost of Goods Sold (COGS) based on current production technology and costs for inputs. Subsequently we explore various avenues for cutting costs when production takes place in full-scale plants, realised in 2030.

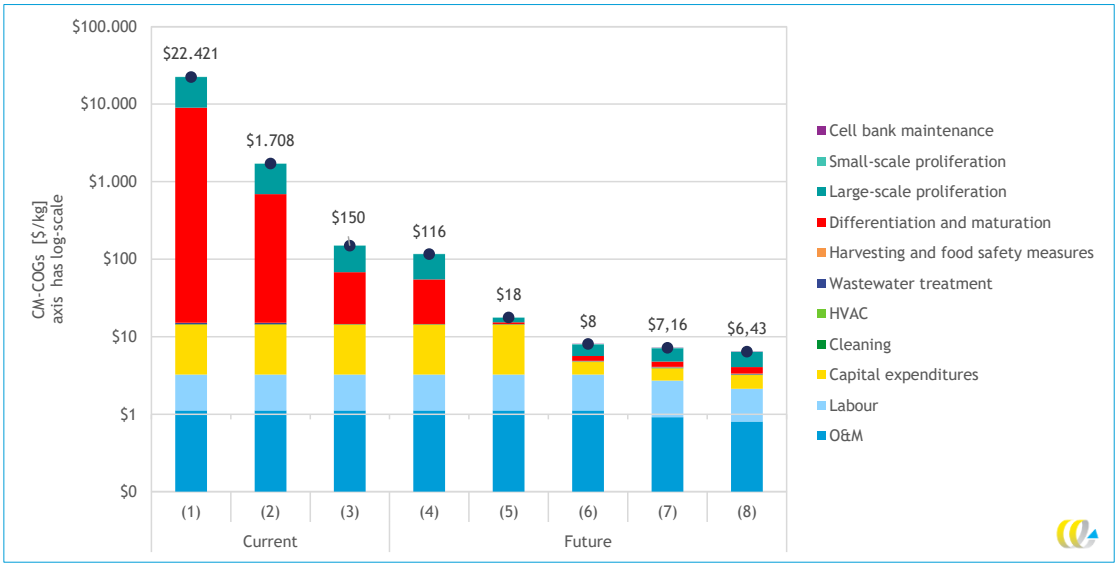
We draw the following conclusions:

- **Current CM production costs** are an order of magnitude of 10,000 to 100 higher than benchmark values for comparable traditional meat products, depending on the exact requirements for medium components and its prices.

- **Future CM production costs**: Substantial cost reductions that bring CM production costs close to the benchmark are feasible (see Figure 2). This requires a combination of reductions that covers nearly all aspects of the business case. Our assessment shows that:
  - Major steps need to be made in reducing the production costs and use of medium ingredients, notably growth factors but also recombinant proteins.
  - Furthermore, the requirements for return on investment need to be set much lower than common practice in commercially motivated investments.
  - The equipment costs for perfusion reactors need to come down.

- Finally, a number of improvements in the production process and favourable choices in cell types will help drive costs down further.

Figure 1 - COGS model of CM ($/kg CM), overview of scenarios (log-scale)[2]



1 Note: This report is one part of the combined Life Cycle Assessment (LCA) and Techno-Economic Assessment (TEA) project. For the TEA, see CE Delft (2021).

2 We have adopted a log-scale, for the costs differ by an order of magnitude of ~1,000; depending on the scenarios assumptions.

Overlap TEA and LCA

At the same time this TEA was carried out, a life cycle assessment (LCA) was also made (CE Delft, 2021). Do conclusions overlap? Can measures to reduce environmental impact also lower costs, and vice versa? Four aspects stand out:

1. **Energy efficiency**: being more energy efficient reduces environmental impact and costs. There still are uncertainties regarding energy use for heating and cooling, and further research into e.g. energy efficient cooling and sustainable heat sources could help reduce both environmental impact and costs.

2. **Energy sources**: a switch to sustainable energy, especially electricity, substantially lowers the environmental impact. The most transparent and robust way to ensure *additional* sustainable electricity production, which actually lowers the national average environmental impact of electricity generation, is taking care of one's own sustainable electricity generation. If sustainable electricity is generated by the CM company on site, this could also mean a reduction in cost compared to either fossil or sustainable electricity purchased on the market.

3. **Medium use**: both increased medium efficiency and increasingly efficient production of ingredients can lower both costs and environmental impacts. Especially regarding certain functional ingredients: the results of the LCA and of the TEA both highlight certain specialty functional ingredients such as recombinant proteins in this regard. A reduction or a switch could mean reducing both impact and costs.

4. **Supply chain collaboration**: To reduce environmental impact and costs further, collaboration in the supply can help lower impact and costs of production of all required substances for CM production. Most notably this is important with regard to medium ingredients, but this reasoning can of course be extended to other inputs (e.g. scaffolds, filtration membranes) as well.

1 Introduction

Numerous innovative companies are currently exploring and developing methods to produce cultivated meat (also called cultured meat, cell-based meat or in vitro meat): meat cells cultivated in cell culture bioreactors, as opposed to on a farm. Clearly, an advantage of cultivated meat (CM) is that it avoids holding animals with the associated risks related to e.g. animal welfare and zoonosis. Furthermore, depending on the type of meat, production process, energy sources used and future innovations, CM holds the potential of a lower environmental impact than conventionally produced meat (CE Delft, 2021).

For CM's potential to materialise, both viable business prospects for companies that produce CM, as well as production costs that make CM a competitive alternative on the consumer market are required.

1.1 A techno-economic assessment (TEA)

The maturity of business processes for the production of cultivated meat is increasing fast. Several companies are involved in R&D and piloting activities, aiming to learn from this with the goal of producing CM at industrial scale and competitive prices in the 2030's. To reach this goal, a number of innovations in the production process and a fall of the prices of the main inputs are needed. In this report, we present a techno-economic assessment (TEA) of the cost of producing of CM in a full-scale, industrial installation, in 2030. This TEA consists of a number of scenarios that combine technological innovations with projections for input-prices, to inform a calculation and breakdown of the future cost of the production of cultivated meat.

The goal of our assessment is to get a better idea of what drives the costs of producing CM, what kind of cost reductions are feasible up to ~2030 and what kind of innovations or input-price reductions would be needed to generate a competitive price for CM.

Because the CM process is still in development, there is a degree of uncertainty regarding the results. Where possible we have included ranges and interpretation of such ranges and the uncertainties. Therefore, the results presented here should not be interpreted as 'the truth', but rather as a good indication and a basis to assess CM production costs, and the possibilities and focus areas for further cost reductions and improvement of the CM process in the future.

1.2 Clients, partners and roles

This study was commissioned by The Good Food Institute. While expertise from this organisation was relevant in the research process, CE Delft was independent in carrying out the research and primary data from (CM and other) companies was not shared with the client. Over sixteen companies (both CM developing companies and companies active in the supply chain) were involved in this project to provide data, for modelling and crosschecks. A reference to sources is included in the annexes.

1.3 Reading guide

In Chapter 2 we describe the methodology used and the process followed for data inventory and data sources. Because much of the data gathered is confidential, this report does not include a full data inventory (a summary is given in the annexes). In Chapter 3 we describe the results of the TEA in the form of cost of good-models for CM production in different scenarios for costs of input and the efficiency of the production process. Chapter 4 provides a sensitivity analysis of the results. In Chapter 5 we present conclusions and discussion.

2 Methodology and inventory

In this chapter, we elaborate on the methodology used to assess the future costs of the production of cultivated meat (CM) and the process of data inventory.

CE Delft has presented the environmental effects of CM in their report 'LCA of Cultivated Meat' (CE Delft, 2021). The methodology and research deployed for both studies overlap substantially. In this chapter, we present the methodology and inventory for the TEA. We include relevant sections from the LCA report (CE Delft, 2021).

2.1 Goal and Scope

This study is a TEA of the production of CM. The goal of the study is to gain insight into the costs of CM production, into the contribution of different processes and inputs to costs (a breakdown of the costs) and the impact of a number of potential innovations in the production process and price reduction of production inputs.

We provide the insights in the form of a model for Cost of Goods Sold (COGS). A COGS model is a breakdown of the direct costs that companies make for producing the goods they sell. We include the cost categories mentioned in Text box 1, but exclude indirect expenses, like distribution costs, sales costs and marketing expenses.

Text box 1 - Costs included in the COGS model

Direct cost categories included in the COGS model

- capital costs;
- operation costs:
  - material inputs;
    - culture medium inputs;
    - electricity;
    - heat;
    - other material inputs, such as chemicals, filters, scaffolds, vials and water (ultrapure);
  - staffing for operation of the plant;
- wastewater treatment;
- maintenance.

We include these costs for the production stages:

- HVAC;
- cell bank maintenance;
- small-scale proliferation;
- large-scale proliferation;
- differentiation and maturation;
- harvesting and food safety measures;
- cleaning;
- wastewater treatment.

As CM is still in development, we model a future commercial scale production facility which reflects expected changes, both internally (the scaling up of CM production) and externally (e.g. share of sustainable sources in electricity mix).

Modelled product

We present the costs of producing 1 kg of a non-specific type of CM, that has the form of a slurry or paste made out of meat cells (comparable to very finely ground meat) suitable for further formulation into meat-consumer products. The mass percentage of water in this product is 70% (baseline) to 77% (low-medium scenario, see Chapter 3).
For further information we refer to the LCA report (CE Delft, 2021).

Scope of costs included

We include costs associated with meat production from basic input up to production of the modelled product. Costs for packaging and transportation to the food-processing industry are not included. This means that all costs associated with process inputs and outputs up to the meat leaving the facility are considered. Further formulation, processing, packaging and post-production transport are outside the scope. The baseline scenario considers a CM product of a meat product, cultivated around 37°C. Model inputs, besides energy demand for heating, are based on inventory data from both land-based and water-based animals.

Because of data confidentiality, no division into different types of meat (e.g. beef, chicken) is possible at the moment, as the number of data sources per type of cultivated meat is limited. Presenting results per type, if possible (because of data availability), would therefore for some types mean presenting results for a specific company, which we do not do in this report. Therefore, the results do not represent the COGS of a specific product developed by a specific CM company, and may not be interpreted as such. Furthermore, the results should, be interpreted as estimates, rather than very precise calculations.
CM companies can use the results to gain insight into factors that may contribute (significantly) to their costs, or extract recommendations for focus areas for future exploration within their product development and for product improvement.

2.2 Inventory

To ensure a robust model and robust results, we contacted over sixteen companies that (aim to) have a role in the CM supply chain for price data. These main data suppliers and their expertise to the data inventory are listed in Table 1.

Table 1 - Partnering companies and institute, and their contribution to the data inventory for the TEA

Company or institute	Expertise
A*star	Cultivated meat research institute (Avian)
Aleph Farms	Cultivated meat production (Bovine)
Avant Meats	Cultivated meat production (Fish)
Mosa Meat	Cultivated meat production (Bovine)
Shiok Meats	Cultivated meat production (Crustacean)
SuperMeat	Cultivated meat production (Avian)
Wild Type	Cultivated meat production (Fish)
Akron Biotech	Recombinant proteins, scaffolds, cell banking systems
Black & Veatch	Consulting engineering and design-build services
Buhler	Extrusion and feed pre-mix
Cell-trainer Biotech	Consulting engineering
Evides	Water production and treatment

Company or institute	Expertise
Merck[3]	Cell culture media and other process related products (e.g. equipment and filters)
OSPIN	Bioreactors and tissue chambers for cell expansion and differentiation
Richcore	Recombinant proteins
Warner Advisors	Consulting engineering

Inventory data was shared confidentially. Therefore, this report does not include an extensive data inventory, but only ranges, averages and median or mode values, depending on the nature of the data. In the Annexes the inventory data we can share are summarised.

2.2.1 Inventory data: quality

Gathering inventory data from multiple (CM and other) companies allowed us to do crosschecks, make mass and energy balances and make a robust model. The inventory included both inquiry into the current situation, and a projection of future potential. These projections were crosschecked, and discussed with the relevant experts (from supply chain companies and research organisations). For some future projections publicly available data were used, for example for the expected costs of the average electricity mix in 2030 (see Section 2.2.2).

A generic inventory questionnaire was sent to CM companies twice, to which most companies also responded twice. All supply chain companies listed in Table 1 were contacted with general questions, after which specific aspects of the production process were discussed further with certain experts. In general, important variables such as volume, cell density, production time, quantity of medium, medium composition, were based on the input of ~five to fifteen companies (CM and non-CM based on topic). Specific values, such as inputs for wastewater treatment, energy use have mostly been determined based on the expert judgement, crosschecked by other independent experts and/or literature.
In Annex A we present a full inventory list (not quantified) and an assessment of data quality is given.

Background databases used for the LCA are Ecoinvent 3 (Wernet et al., 2016), version 3.6 (allocation cut-off by classification), and the Agri-footprint database (Durlinger et al., 2017) (version 4.0, economic allocation).

2.2.2 Price data

To collect prices for the various inputs, we have used the sources listed below.
For a detailed overview of values and sources, please see the annexes:

- Energy prices: World Energy Outlook and calculations by CE Delft.
- Prices for medium ingredients: Alibaba, quotes from individual suppliers (incl. projections for price development towards 2030), literature.
- Investment, maintenance and staffing: engineering experts.
- Wastewater treatment: calculations by CE Delft based on COD and O_2 demand for organic N and free NH_3.

[3] Merck KGaA, Darmstadt, Germany Emdgroup Reserach Innovation-field cultured meat

2.3 System and system boundaries

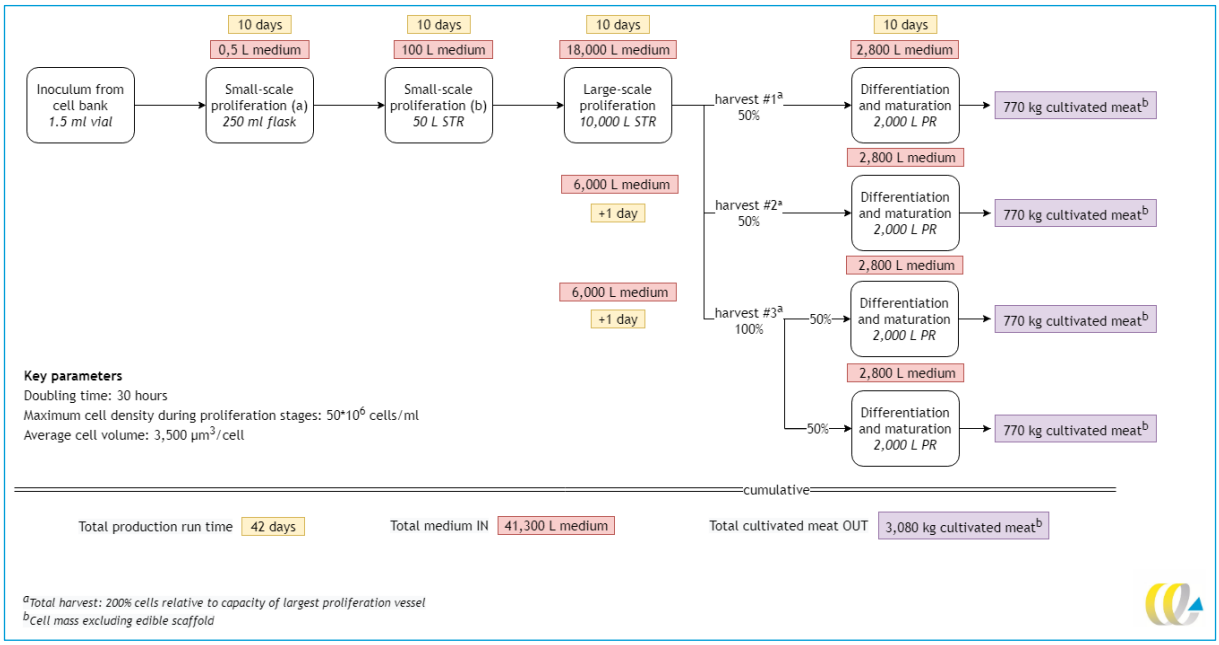
2.3.1 Main parameters for model of production process (baseline scenario)

We modelled production of CM for a future situation, in which production is scaled up to a production unit of 10 kton per year. The theoretical baseline production line is described below and in Figure 2. This design of the production process is based on Specht (2020), adapted in some aspects for the purposes of this study.

The input data for the model is based on company data, as described in Section 2.2. The baseline parameters for the model are reported in Annex A. The baseline parameters are based on representative averages, or in some cases median or mode, values (depending on the spread). It is important to note that the values used in this study do not represent any single production system and the values can therefore not be interpreted as being fully representative for the product system of any of the companies involved in providing data.

The process (schematically shown in Figure 2) is semi-continuous with three intermediate harvests. Proliferating occurs until the largest stirred-tank reactor (STR) volume (working volume 10,000 L) is filled, at which point 50% of the cells are harvested, the medium is refilled, and cells again proliferate until maximum density is reached. This repeats a total of three times, in total ensuring 200% (relative to the largest proliferation reactor: 50% + 50% + 100%) of cells are harvested. Harvested cells are seeded onto scaffolds in perfusion reactors (PR). This production line has a total of 4 PRs (working volume 2,000 L, each containing 50% of the harvest) installed in parallel. After each production run (for the 10,000 L STR this is twelve days, for each of the PR this is ten days) the reactors are cleaned using a clean-in-place and steam-in-place (CIP/SIP) system. The total production time from cell vial to harvest is 42 days. Around 130 of these production lines are assumed to be operating in parallel to meet the demands of 10 kton annually set forth in the study.

Figure 2 - Baseline production line, semi-continuous with three intermediate harvests



2.3.2 Capital expenses and investments

We have translated the production line into the requirements for equipment for a full-scale facility (see Table 2).

Table 2 - Main equipment requirements for a 10 kton CM production facility

Equipment type	Pieces of equipment needed
Perfusion Reactors 2,500 L (working volume 2,000 L)	430
Stirred-Tank Reactors 12,500 L (working volume 10,000 L)	130
Stirred Tank Reactors 60 L (working volume 50 L)	107
Storage and mixing tanks for culture medium 60,000 L	15
Clean-in-place system	1

Based on the equipment needs, we have assessed the investment required to build a facility that produces 10 kton of CM. To assess the investment costs, we have used the following assumptions:

- We assume the hygiene standard for the production process is food grade, not pharmaceutical grade.
  That means it adheres to cleanliness and hygiene standards that are common practice in aseptic-aerobic precision food fermentation (certain enzymes, food proteins, antibiotics, amino-acids)[4] where maintaining a sterile boundary is key. This is accomplished by the following industry standard processes, used in industrial production facilities for the above mentioned products:
  - frequent cleaning and steam sterilization (> 135 degree Celsius) of bioreactors and piping;
  - surface treatments of reactors such as electropolishing and acid passivation,
  - pressurised STR's;
  - sterilization of medium, mostly through heating, through filtration for some heat-sensitive ingredients;
  - highly automated facility (e.g. cleaning sequence).

  It does not include[5]:
  - adherence to FDA-standards for drug production;
  - clean rooms.
- We have taken benchmarks for cost estimates from bioprocess industry in food sectors.
- Cost estimates are at FEL[6]-1 stage. That means they are based on the scope definition of the system as defined in Table 1 and Section 2.3.1. The major cost determinant is the amount and size of reactors. Equipment cost estimates for STR's, storage and mixing tank and CIP/SIP should be considered FEL-1, hence an uncertainty bandwidth of unit costs of -20% to +40%, but prices are conditional on development of steel prices towards 2030. The estimated value for the perfusion reactor has a larger uncertainty bandwidth.
- We multiply the bare equipment costs (including agitation and basic equipment) with an installation factor (Lang-factor, see Annex C). The installation factor includes costs for placement, instrumentation, piping, electrical, buildings, engineering and contractors. It differs depending on the extent to which the equipment comes in a package or is pre-instrumented.

[4] The production of certain amino-acids (e.g. lysine) is sensitive for contamination, yet it takes place in facilities with non-pharma hygiene standards comparable to the ones we have adopted for CM production.

[5] There are currently many examples of cell cultures in "open" lab facilities.

[6] Front end loading.

- We calculate the capital costs that are associated with the investment needed, using a payback time criterion for the project as a whole. Advantages of this criterion are its ease of calculation and that it is easy to interpret. A drawback of payback times is that it does not take into account time preferences of project revenues. To overcome this drawback, in industrial practice it is more common to use the (internal) project profitability as the criterion. The project profitability should then be higher than the weighted average of interest rate (external financiers) and demands for return on equity (internal financiers). However, this criteria has the drawback that it is harder to interpret and more complex to quantify. For this project, and given the rough nature of the assessment of investment costs, it is sufficient to show the impact of a difference in payback time as an example of how different investment requirements impact the cost of CM production.

Annex C provides more detailed assumptions and sources for equipment costs.

2.4 Limitations of the research

We have made a major effort to obtain values for equipment and input requirements as well as prices for all identified inputs. We did not, however, obtain these for all identified inputs. Hence, a small number of cost components were not taken into account, because of data limitations on prices or requirements for pieces.
Based on expert judgment, we estimate that including these components would not alter the conclusions, please see Annex D for an overview.

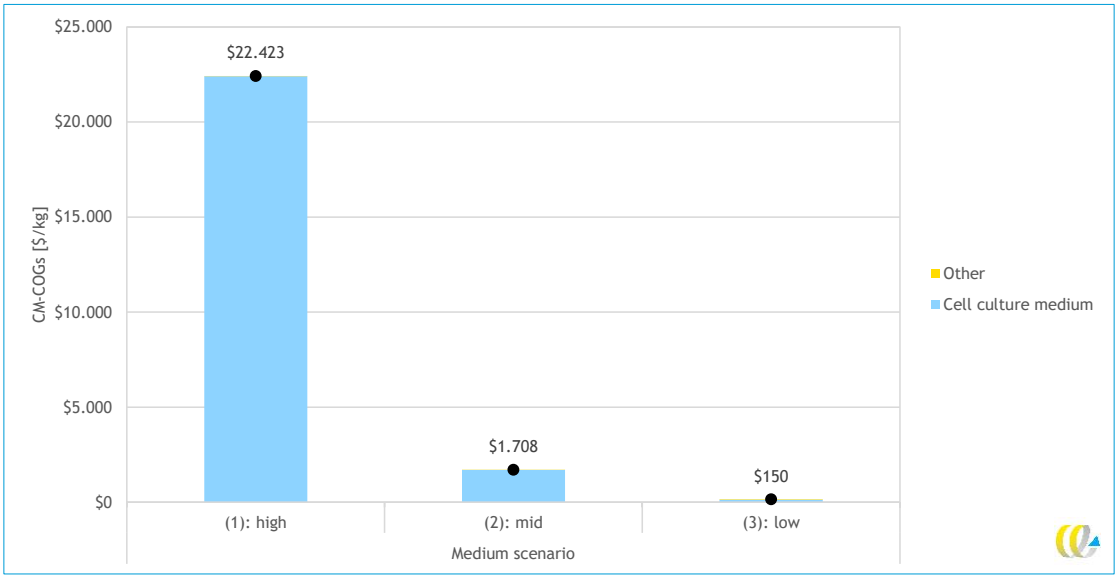
3 Results

In this chapter, we first present a baseline TEA, based on current prices (Section 3.1). These cost projections are a benchmark for further analysis: they represent the starting point on which we plot the scenarios for cost reduction in Section 0.

3.1 COGS Cultivated meat production system - baseline

Figure 3 shows that cell culture medium accounts for the vast majority of costs of CM.

Figure 3 - COGS model of CM [$/kg CM], per input type - baseline scenarios



Because medium is the driver for costs, we present three baseline scenarios for CM production costs, that differ in the amount and costs of medium:

- High: Relatively inefficient use of medium and high prices for individual ingredients, representing the upper bound of obtained data.
- Mid: Average composition (based on the geometric mean of obtained data[7]) and prices.
- Low: Relatively efficient use of medium and low prices for individual ingredients, representing the upper bound of obtained data

Annex B provides a detailed overview of the composition and ingredient prices in the scenarios and the total amount of ingredients needed for the production of 1 kg of CM in these scenarios. The large variation in results as observed in Figure 3 is mainly caused by large variation in quantity of recombinant proteins needed for CM production, specifically albumin. Primary data suggest there are different ideas as to what extent albumin is needed in the medium, and to what extent this can be left out or replaced. The scenarios reflect this.

[7] The geometric mean was used in order to best reflect the distribution of obtained data.

For the prices of the ingredients, we adopt a bandwidth based on public market sources, scientific literature and quotes from industry. The major cost driver is recombinant proteins, while the second major cost driver are the specific growth factors. Together, these ingredients represent > 99% of medium-costs; recombinant proteins accounts for around 80% of medium costs. Table 3 shows the prices we adopt for these ingredients.

Table 3 - Prices for cost drivers of medium

	$/g ingredient		Sources
	Low	High	
Recombinant proteins			
Albumin	41	400	Invitria[8] & Specht (2020)
Insulin	155		Invitria[9] & Specht (2020)
Transferrin	246		Northwestern Medicine[10] & Specht (2020)
Growth factors			
FGF2	1,315,000	2,340,000	Orf Genetics[11] & Specht (2020)
TGF-ß	3,650,000	4,950,000	Qkine[12] & Specht (2020)

Notes:

- Mid-prices are calculated as a geometric average of low and high. Bulk pricing discounts were not considered in our calculations.
- Low prices based on published quotes accessed in the first week of December 2020.

In this study, we model five total recombinant proteins and growth factors in the cell culture media, which we believe to be a reasonable number based on conversations with industry experts and data partners. We anticipate that albumin, insulin, and transferrin will be among the most common recombinant proteins included in cultivated meat cell culture media. We selected FGF2 and TGF-ß as examples of common growth factors found in stem cell media (Specht, 2020).

It must be noted that media used by cultivated meat manufacturers may contain different types of growth factors and recombinant proteins than the ones specified in this study, and these different types may have different associated costs. The total number of recombinant proteins and growth factors included in some cell culture media formulations may be fewer or greater than 5. The full range of possibilities was not considered for this study.

We observe that CM production costs are well above the market benchmark of around $ 2/kg (Risner et al., 2021) even in a low-medium scenario. In the following section, we explore avenues that may reduce the costs towards this benchmark.

8 InVitria Products : Cellastim S

9 InVitria products : Optiferrin® Recombinant human transferrin

10 Feinberg School of Medicine, Paul Burridge Lab : B8 index

11 ORF Genetics product : MESOkine - FGF-basic

12 Qkine product : recombinant human tgf b1 plus protein

3.2 Scenarios for future cost reduction

In this section, we discuss a number of scenarios for future cost reductions (~2030). Figure 4 presents an overview of these scenarios and their impact on the costs of CM production in different production phases and for different cost components (see Section 2.3). We use a log-scale, because CM production costs differ by a factor ~1,000 going from the first scenario to the scenario that combines all possibilities for cost reductions.

The first three scenarios have been discussed in Section 3.1. The latter six scenarios show the impact of possible future avenues for cost reduction[13]. In this section, we present a synopsis of the analysis. In the next sections, we dive into a more detailed description per scenario.

Text box 2 summarises the main assumptions and differences between the nine scenarios.

Text box 2 - Summary of scenarios analysed in this chapter

Baseline scenarios
(1): scenario based on high-medium usage and high current prices for medium ingredients.
(2): as (1) + mid-medium usage and mid current prices for medium ingredients.
(3): as (1) + low-medium usage and low current prices for medium ingredients.
These scenarios are described in Chapter 2 and Section 3.1. They all adopt commercial investment criteria and the standard values for cell density, production run time and cell volume as used for the LCA model (CE Delft, 2021).

Scenarios for cost reduction
(4): as (3) + lower prices for specific growth factors.
The lower prices are assessed as feasible in 2030.

(5): as (4) + lower costs for recombinant proteins.
Reductions in the use of recombinant proteins and lower production prices assessed as feasible in 2030.

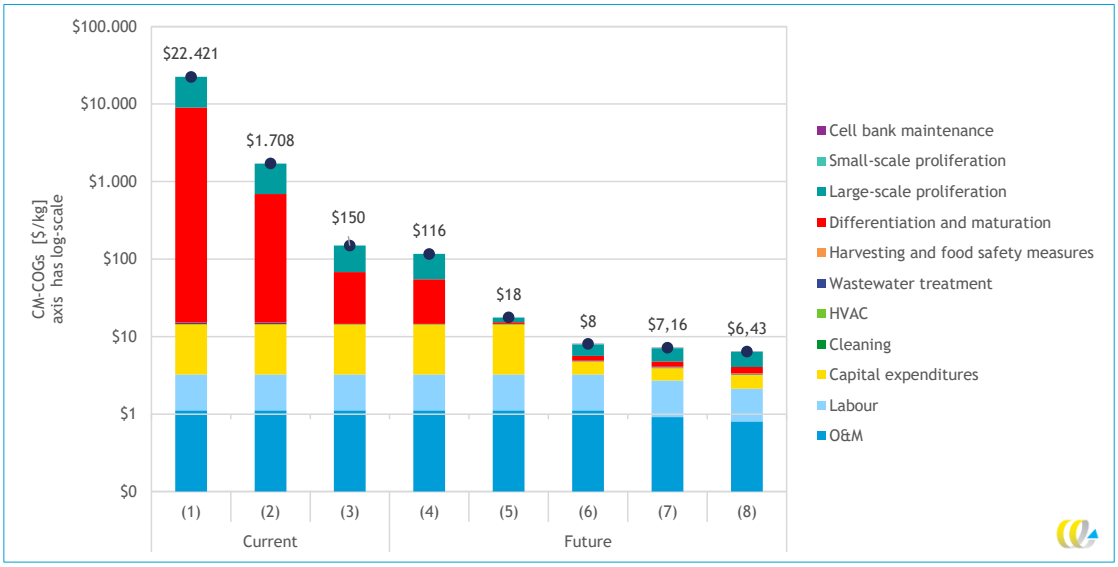
(6) : as (5) + social investment criteria.
Reductions in capital expenditures because of more relaxed, but feasible, criteria for return on investment.

(7): as (6) + shorter production run time.
More efficient CM production process that leads to reductions in media use, equipment requirements and energy use.

(8) : as (7) + larger cell volume.
More efficient CM production process that leads to reductions in equipment requirements and energy use.

[13] The medium scenarios and the scenarios for shorter production run time and larger cell volume are adopted from the sensitivity analyses in the LCA study.

Figure 4 - COGS model of CM ($/kg CM), overview of scenarios (log-scale)[14]



Notes:

(1): scenario based on high-medium usage with high current prices; commercial investment criteria and standard values for cell density, production run time and cell volume (see Annex B and next sections for more details).

(2): as (1) + with mid-medium usage with mid current prices.

(3): as (1) + low-medium usage with low current prices.

(4): as (3) + lower prices for growth factors.

(5): as (4) + lower costs for recombinant proteins.

(6): as (5) + social investment criteria.

(7): as (6) + shorter production run time.

(8): as (7) + larger cell volume.

See Text box 2 for a short description of the scenarios and annexes and next sections for more details.

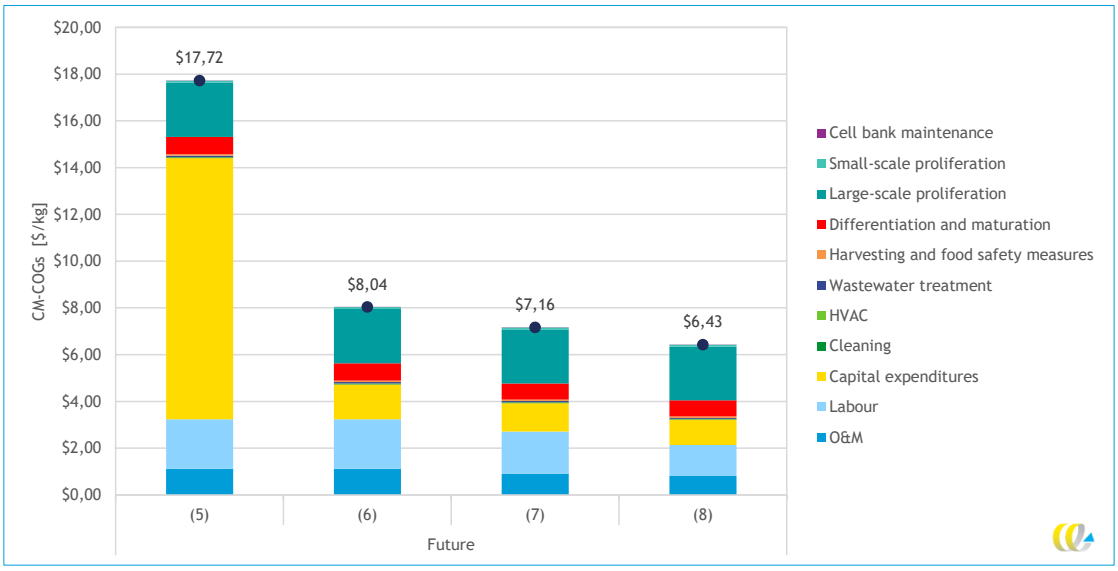
Figure 4 shows that, based on current market prices for medium ingredients, the costs for CM production remain well above $ 100 per kg, even in a scenario with low current prices and low-medium use (Scenarios 1-3).

The major cost drivers for medium are specific growth factors and recombinant proteins (primarily albumin). In Scenarios (4) and (5), we analyse the impact of cost reductions for these two components. Reducing the costs of growth factors has a substantial impact on CM costs (as in e.g. (Specht, 2020)), and limiting the use of recombinant proteins (primarily albumin) together with reducing the production price seems even more vital to bring CM production costs down. If we combine cost reductions for growth factors and recombinant proteins (Scenario 5), we assess CM production costs to be around $ 15. Although already a reduction with a factor 100 compared to baseline scenarios, it is still an order of magnitude higher than market costs for comparable meat products (around $ 2/kg).

[14] We have adopted a log-scale, for the costs differ by an order of magnitude of ~1,000; depending on the scenarios assumptions.

In Figure 5 we zoom into the scenarios for further cost reductions (Scenario 5-8).

Figure 5 - COGS model of CM ($/kg CM), overview of scenarios with potential future cost reductions



Notes:

(5): scenario based on low-medium usage with cost reductions for growth factors and recombinant proteins and low current prices for other ingredients; commercial investment criteria and standard values for cell density, production run time and cell volume (see annexes and next sections for more details).

(6): as (5) + social investment criteria.

(7): as (6) + shorter production run time.

(8): as (7) + larger cell volume.

See Text box 2 for a short description of the scenarios and annexes and next sections for more details.

We observe that the major cost component in Scenario 5 is the recuperation of investment costs. Scenario 5 assumes commercial investment criteria for the recuperation. Scenario 6 adopts a more social approach to investment criteria (recuperation over the lifetime of the facility). This makes the CM price fall below the $ 10 threshold.

Scenarios 7 and 8 add economic gains from a shorter production run time and a larger cell volume. These make production costs fall some more, to reach a lower limit of around 6 $/kg CM[15].

In the following sections, we describe the different scenarios and their impact on costs in more detail.

[15] In Section 4, we present the impact of these in a scenario where a commercial investment criteria is adopted.

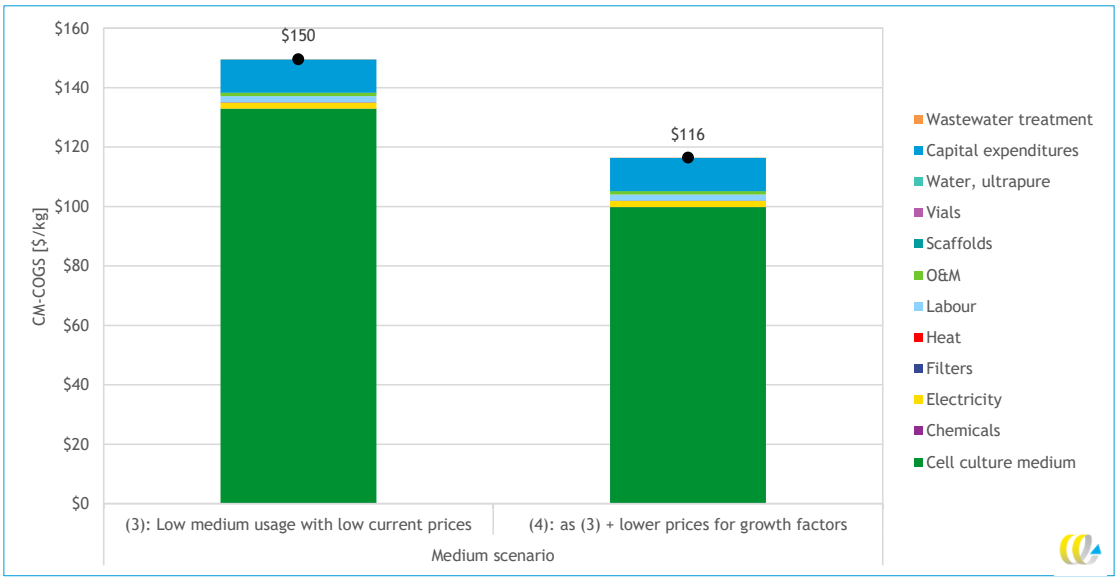
3.2.1 Scenario 4: Growth factors

In Section 3.1 we have seen that medium is the major cost driver of CM production costs. This is corroborated by previous literature (e.g. Specht, 2020, Stephens et al., 2018). We first explore the potential for cost reduction by price reductions of growth factors. As in other literature, we adopt the scenario that a price reduction of a factor > 1,000 may be possible. This may be feasible when growth factors are produced at larger scale and produced through recombinant expression, similar to recombinant protein production for industries such as food processing, consumer products and paper milling. These proteins (often enzymes), that are comparable to the growth factors for CM production, are produced at much lower costs than we adopt for the growth factors in Scenarios 1-3 (Specht, 2020).

In comparison with Specht , our adoption of a price reduction with a factor 1,000 is conservative. However, such a reduction already leads to costs for growth factors so that they are no longer a major cost driver in CM production.

Figure 6 presents that cost reduction that is feasible with future reductions in the prices for growth factors. We see that medium is still a major cost driver; that is because the majority of medium costs in our medium formulation stem from recombinant proteins. In the following section, we explore options for reducing this cost component.

Figure 6 - COGS model of CM ($/kg CM), per input type - impact of price reduction in growth factors



3.2.2 Scenario 5: Recombinant proteins

In the previous section, we have explored the effect of a future cost reduction in the price of growth factors (Scenario 4). In this section we explore the impact of a reduction in costs of recombinant proteins on top the price reduction in growth factors.

The medium contains a number of recombinant proteins ingredients, such as:
- albumin;
- insulin;
- transferrin.

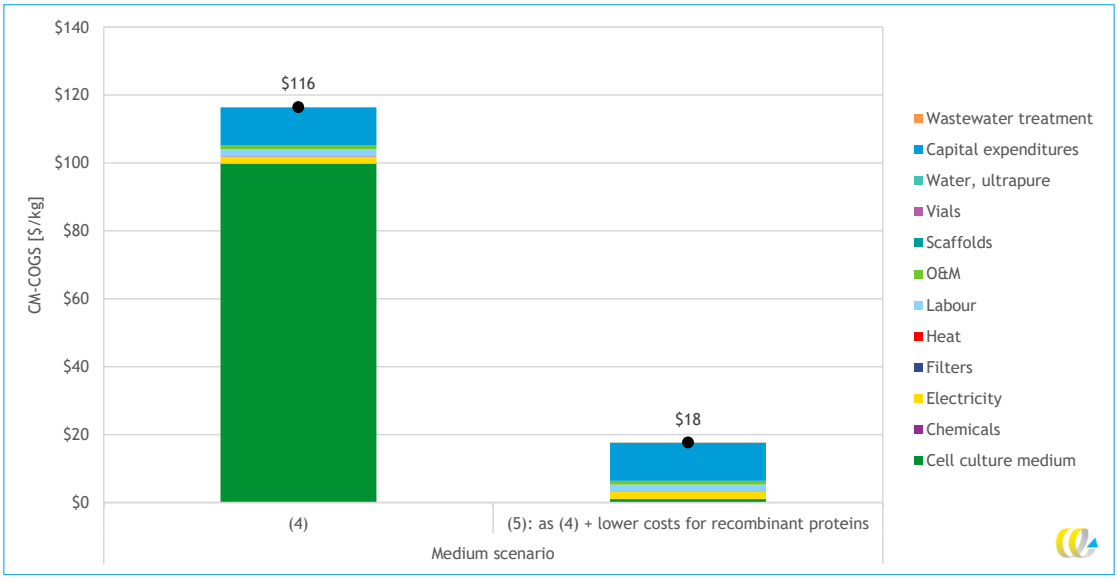
Of these, albumin is the main cost driver. In the mid and high-medium scenarios, >95% of the recombinant proteins is albumin. In the low-medium scenario, this drops to around 80%. In the case that albumin can completely be removed from the growth medium (and is not replaced by other ingredients) a similar price drop could be expected.

To reduce the cost of albumin, there are two options.
First, the use of albumin may be reduced. The albumin requirements may differ per type of meat that is produced and per process design that is adopted. Indeed, our CM industry data shows that the albumin requirements differ substantially from one company to the other, and companies indicate this is a point of optimisation.

Clearly, if we reduce the amount of albumin, it needs to be replaced by another type of protein; hence we adopt the conservative assumption that requirements for the amount of recombinant proteins may be reduced by a net factor 5.
Second, the price of albumin production and the production of other recombinant proteins may fall. We have credible industry sources that point towards a feasible cost reduction of a factor 100.

Figure 7 shows the impact of a reduction in the costs of recombinant proteins, on top of the scenario with reduced costs for growth factors.

Figure 7 - Impact of reduction in cost of recombinant proteins ($/kg CM), per input type



We see that reducing the costs of recombinant proteins is a vital step in obtaining CM production costs that come closer to the benchmark for competing meat products.

Figure 8 and Figure 9 depict a COGS model for this scenario (5), looking from the angle of production stages and production inputs respectively. We observe that the major remaining cost driver is the investments costs. We elaborate on these costs in Section 3.2.3.

Figure 8 - COGS model of CM ($/kg CM), per production phase - low-medium use with reduced costs for growth factors and recombinant proteins (Scenario 5)

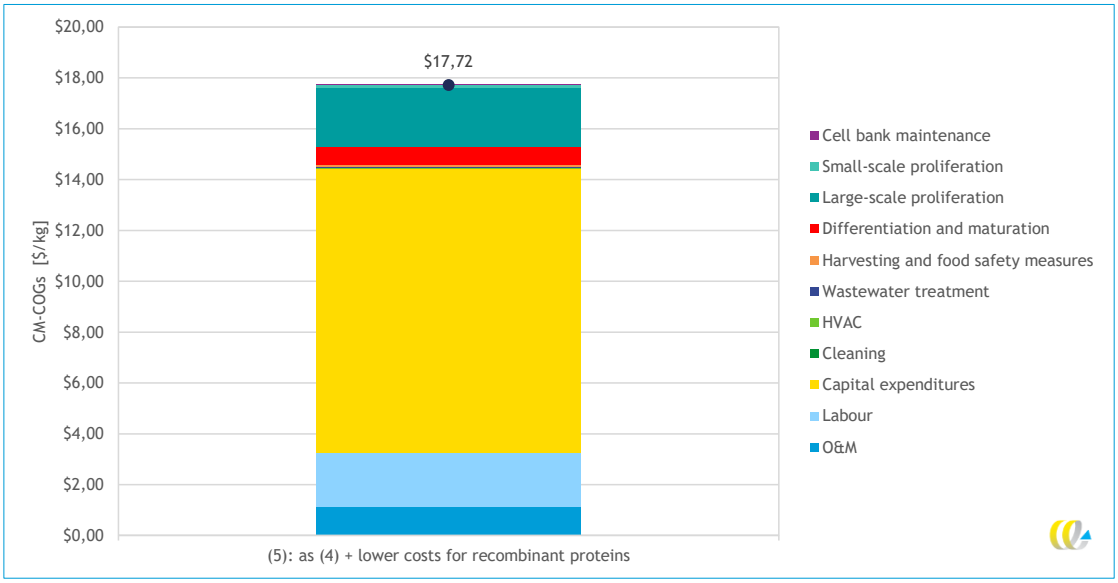
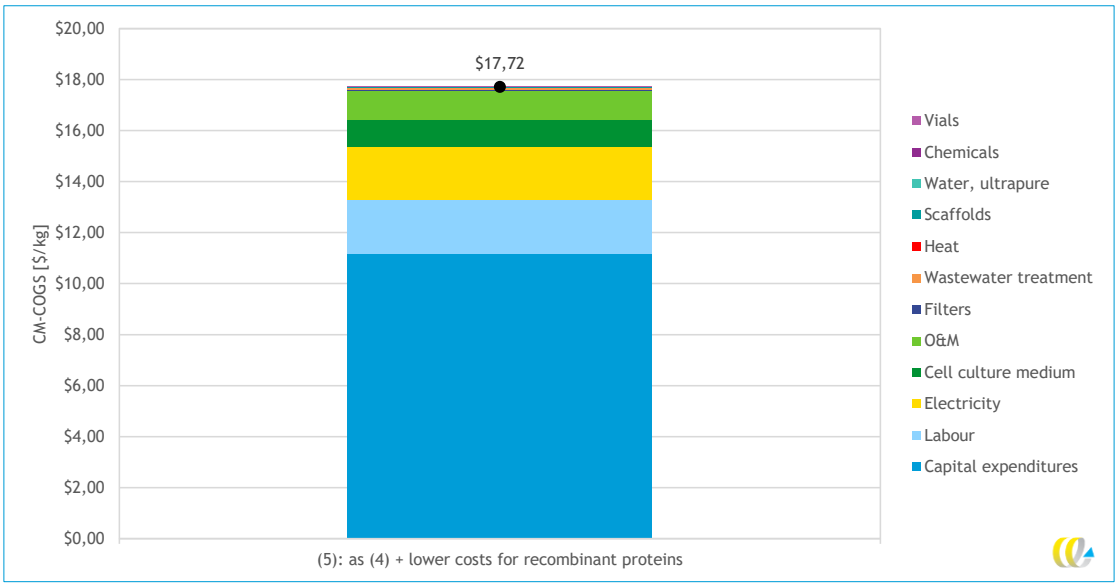


Figure 9 - COGS model of CM ($/kg CM), per input type - low-medium use with reduced costs for growth factors and recombinant proteins (Scenario 5)

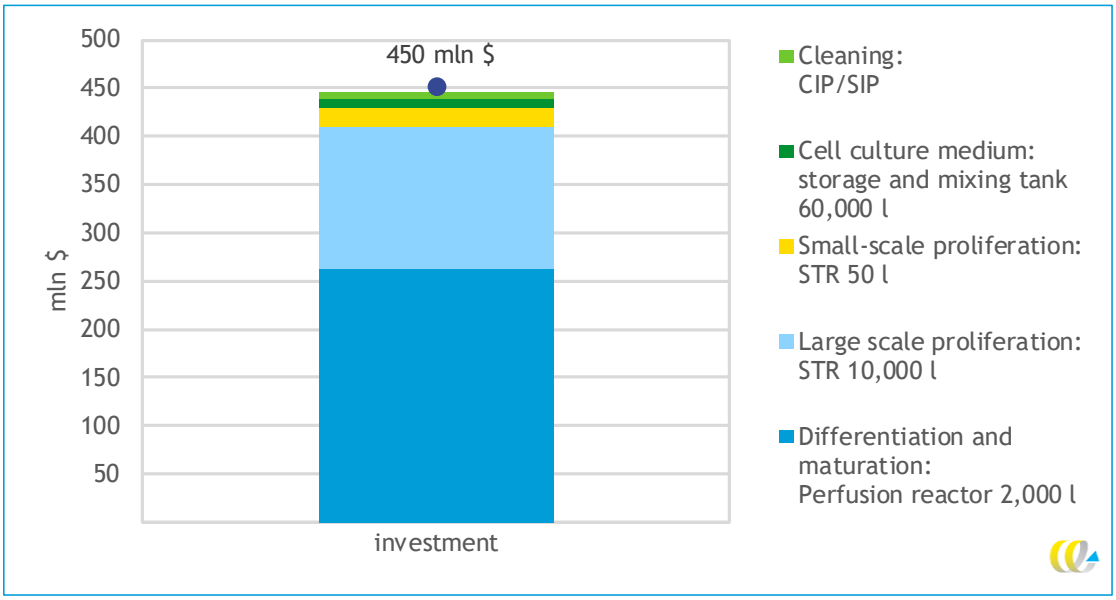


3.2.3 Scenario 6: Capital expenditures

In the previous section, we found that after future reductions in the costs of growth factors and recombinant proteins, medium costs are no longer dominant in the CM-COGS model. Rather, the capital expenditures have become the major cost driver.

This section analyses an avenue for reduction of capital expenditures by relaxing the criterion for the required return on investment. Before we do this, we show our estimate of the investment capital needed, and its breakdown (Figure 10).

Figure 10 - Breakdown of investment costs for an industrial 10 kton CM plant (mln $)



Notes:

- For detailed data and sources, see Annex C.
- Values for standard equipment should be considered FEL-1, hence an uncertainty bandwidth of -20% to +40%, but prices are conditional on development of steel prices towards 2030. Values for perfusion reactor have a larger uncertainty bandwidth.
- For equipment requirements, please see Section 2.3.2.

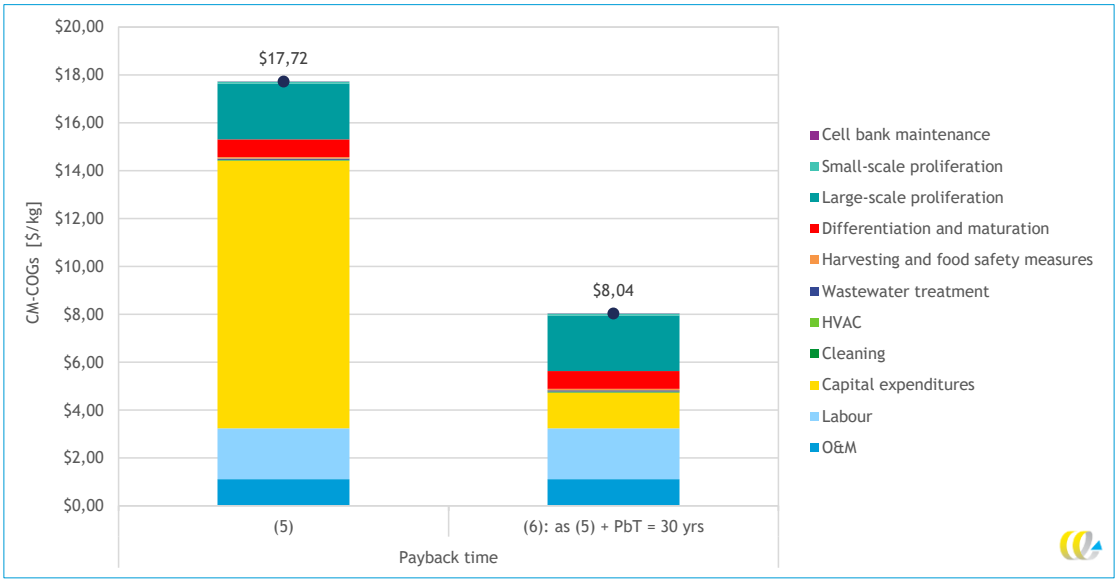
The investment capital assessment is based on the equipment requirements as elaborated on in Section 2.3.2 and Annex C. Equipment and installation costs are based on assessments from industry and engineering experts, and include equipment purchase costs (including agitation and basic instrumentation) and an installation factor (Lang-factor).
The installation factor includes costs for placement, additional instrumentation, piping, electrical, buildings, engineering and contractors.
Investment capital needs for a 10 kton CM production plant are estimated to be around $ 450 mln.
The staffing requirements for this installation we estimate to be around 200. This assumes 24/7 operation in shifts and includes operators, lab, managers and small maintenance.
Yearly costs for large maintenance are estimated to be around 5% of bare equipment costs, all in.

Scenario 5 in Figure 11 and Figure 12 adopts the position that these costs should be recuperated at a commercial rate. For this project, it is sufficient to show the impact of a difference in payback time as an example of how different investment requirements impact the cost of CM production. Typically, the hurdle for commercial investment projects to get funded is payback time < 4 years[16]. In Scenario 5, we have adopted a commercial payback time of 4 years.

[16] In this analysis, we use the payback time as the investment criterion. Advantages of this criterion are its ease of calculation and that it is easy to interpret. A drawback of payback times is that it does not take into account time-preferences of project revenues. To overcome this drawback, a more common investment criterion that is used, is the (internal) project rentability. The project rentability should be higher than the weighted

There are a number of reasons why the hurdle for the payback time may be relaxed. First, it is likely that investors in CM production facilities do not only have a commercial motive, but also a social motive (animal welfare, environmental footprint). This may lead them to be less stringent on the financial profits of the investment. Furthermore, CM production processes are developing rapidly and may continue to do so in the future. Taking a lead in upscaling CM production to an industrial scale may generate benefits in terms of learning and experience that allow for an investor to take a larger risk. Finally, part of the investment costs may be carried by government bodies (e.g. subsidies or participations related to the EU Green Deal) or non-profit funders, that hold much lower demands for financial profits. Because there is uncertainty as to which extent the investment criteria may be relaxed, we show a sensitivity analysis for this in Chapter 4. In the analysis below, we adopt an investment criterion of a required payback time < 30 years.

Figure 11 - Impact of reduction in requirement for payback time, costs per production phase

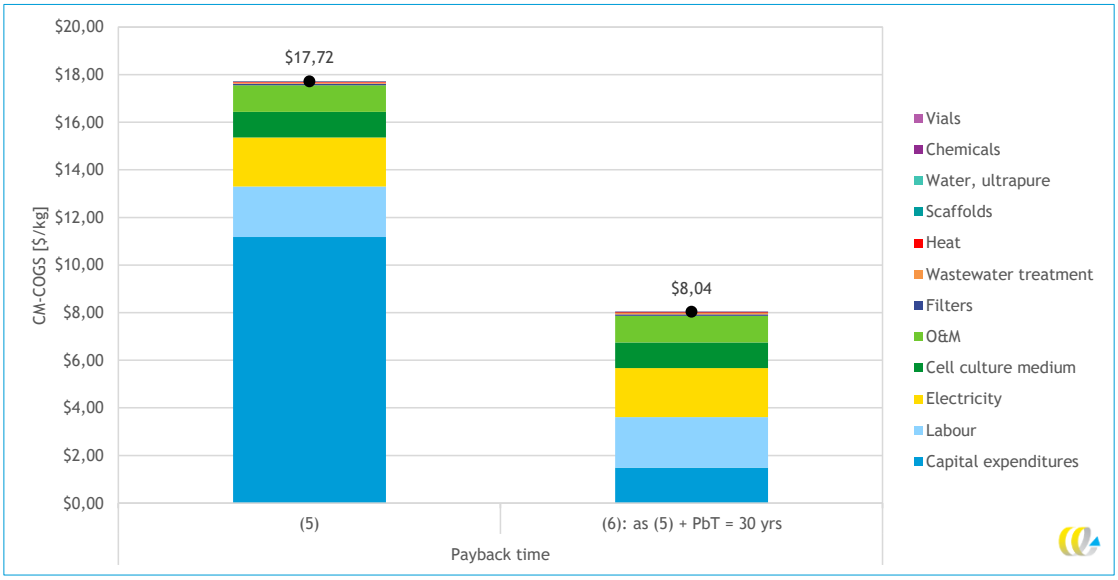


Notes:

- We obtain shares of capital expenditures that are in the same range as (Risner, 2021).
- Total figures for yearly CAPEX are 110 mln (PbT = 4 years) and 15 mln (PbT = 30 years).

average of interest rate (external financiers) and demands for return on equity (internal financiers). However, this criterion has the drawback that it is harder to interpret and harder to calculate.

Figure 12 - Impact of reduction in requirement for payback time, costs per input type



Note: We obtain shares of capital expenditures that are in the same range as (Risner, 2021).

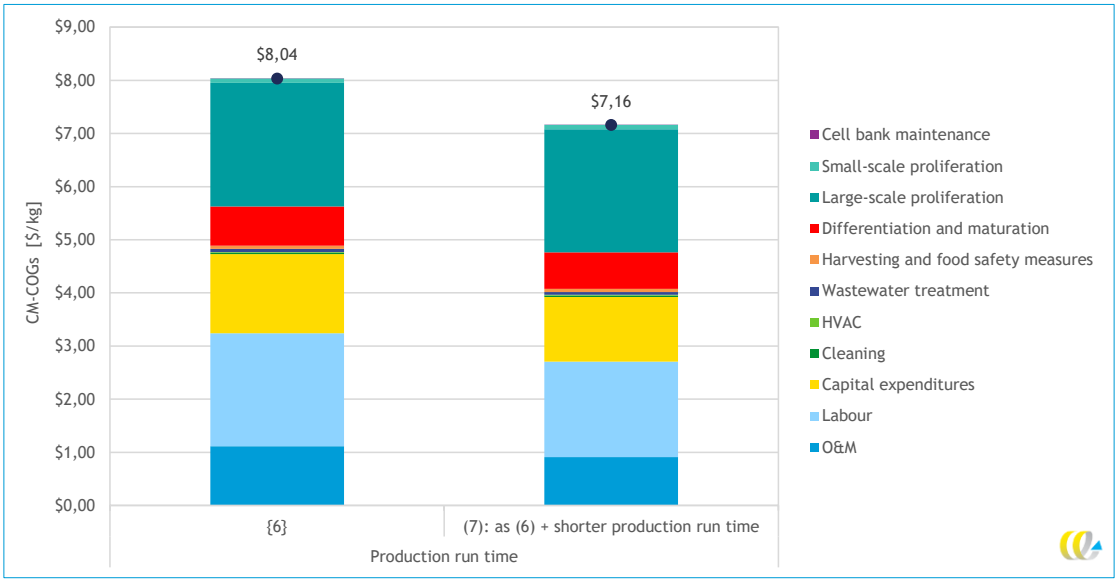
From the figures, we observe that CM production costs again are reduced considerably, reaching the same order of magnitude as production costs for traditional meat alternatives. Also, we observe that there is no longer a single input that is the key driver of production costs. In the following sections, we explore a number of pathways that may help to reduce costs further.

3.2.4 Scenario 7: Production run time

The production run time depends on the doubling time (for proliferation stages) and on the desired maturity of cells in the final product (for the differentiation and maturation stage). It is estimated that a reduction in production run time of 25% is feasible.

Shorter production run time in the reactors reduces overall energy demand, lowers medium demand during differentiation and maturation (we assume a linear relation) and results in a smaller amount of reactors needed to produce the same amount of CM. Figure 13 and Figure 14 depict the effect of shorter production run time, in a scenario with a social investment criterion. In Section 4.2 we show its effect when investors use a commercial investment criterion.

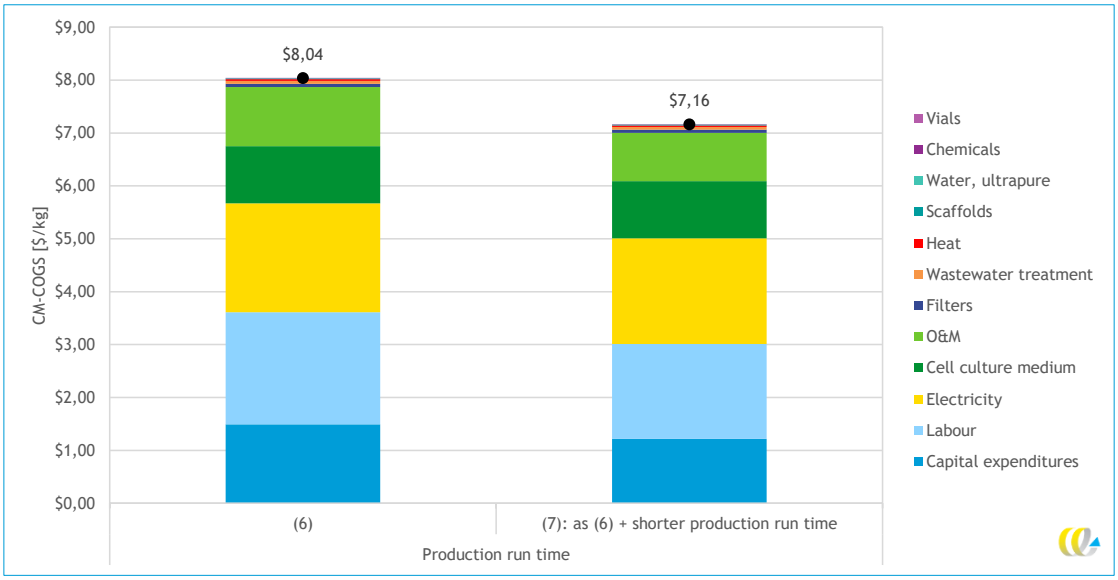
Figure 13 - Impact of reduction in production run time, costs per production phase



Notes:

- Both scenarios based on low-medium use and prices, including future reductions in growth factors and recombinant proteins and thirty year payback time of investment .
- Investment costs drop to 365 mln dollar, staffing drops to 180 fte.

Figure 14 - Impact of reduction in production run time, costs per input type



Notes:

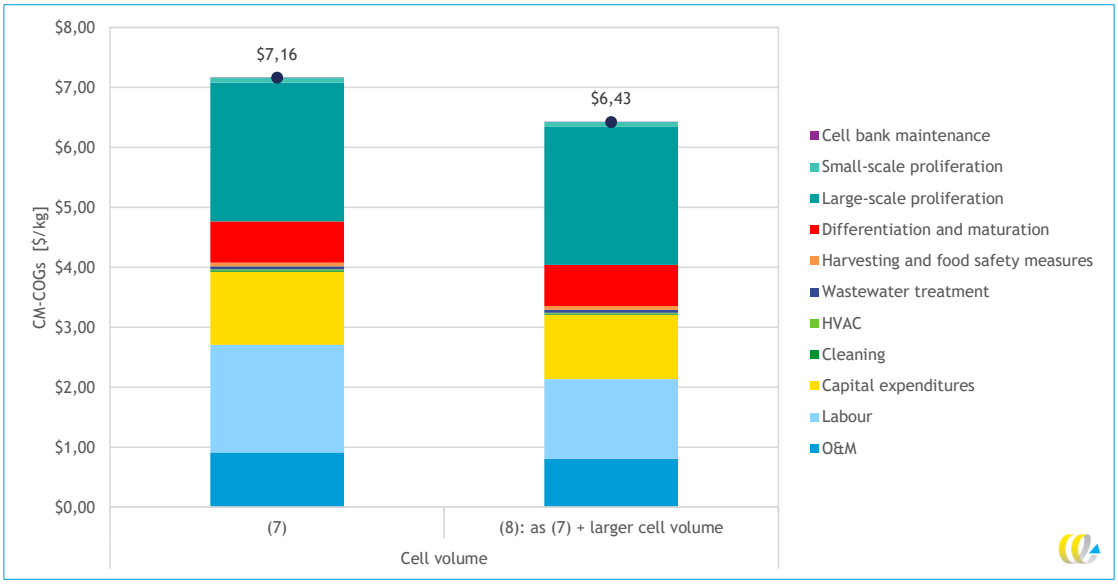
- Both scenarios based on low-medium use and prices, including future reductions in growth factors and recombinant proteins and thirty year payback time of investment.
- Investment costs drop to 365 mln dollar, staffing drops to 180 fte.

3.2.5 Scenario 8: Cell volume

Average cell volume differs per species type and cell type. For example, fat cells are much larger than muscle cells, and within the different types of muscle cells, there is large variation. In addition, small animals tend to have smaller cells than large animals. As the companies involved in this study produce a range of species and cell types, we used an average cell volume for the baseline scenario and determined potential larger cell volume (5,000 μm^3) on primary data collected and literature.

The effects of larger cell volume would mean that more meat cells can be grown in a reactor of the same volume. This lowers energy demand, medium demand as well as equipment requirements. Below, we plot the effect of larger cell volume, when investors adopt a social investment criterion. In Section 4.3, we show the effect when investors adopt a commercial investment criterion.

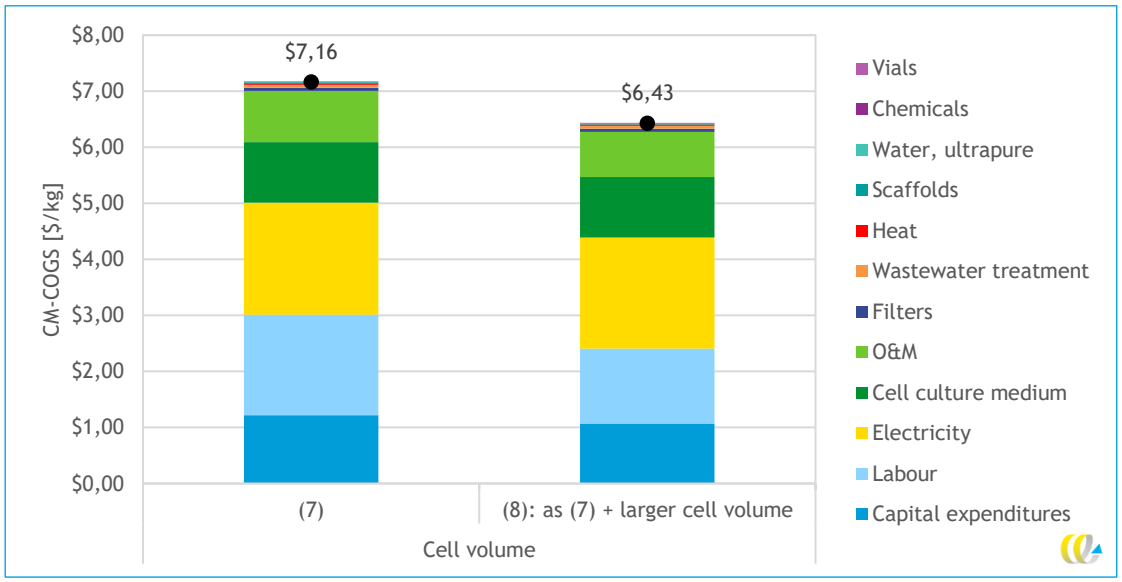
Figure 15 – Impact of larger cell volume, costs per production phase



Notes:

- Both scenarios based on low-medium use and prices, including future reductions in growth factors and recombinant proteins, thirty year payback time of investment and shorter production run time.
- Investment costs drop to 320 mln dollar, staffing drops to 130 fte.

Figure 16 - Impact of reduction in volume of cells, costs per input type



Notes:

- Both scenarios based on low-medium use and prices, including future reductions in growth factors and recombinant proteins, thirty year payback time of investment and shorter production run time.
- Investment costs drop to 320 mln dollar, staffing remains similar to (8): 130 fte.

We observe that production costs of 1 kg of CBM have fallen to $ 6.43.
Furthermore, there are no clear candidates for further substantial cost reduction. We have explored possible avenues for reducing the costs of medium, lowering capital expenses and further improvements in the efficiency of the CM production process. Taken together, these bring production costs of CM in the same order of magnitude as the benchmark value of traditional meat (2 $/kg).

4 Sensitivity analysis

In this chapter, we explore how sensitive the results are for the investment criterion. We do this because we have found that capital expenditures may cover a large part of CBM production costs, notably when cost reductions in medium are accounted for.

Further, we revisit the effects of shorter production run time and larger cell volume in a scenario where the investment criterion is based on commercial considerations. We do this, because these two avenues for cost reduction have an impact on the amount of equipment required and hence influence capital expenditures.

As part of the corrigendum, we have removed the section that explores the sensitivity of the results to increased cell density. We have removed this scenario, because combining a higher cell density with larger cell volume is physically impossible adopting the quantitative assumptions in our model. However, if we adopt different quantitative assumption, some increase in cell density is possible. In the following textbox, we qualitatively describe the effects of increased cell density on the COGS.

Text box: sensitivity of COGS to increased cell density

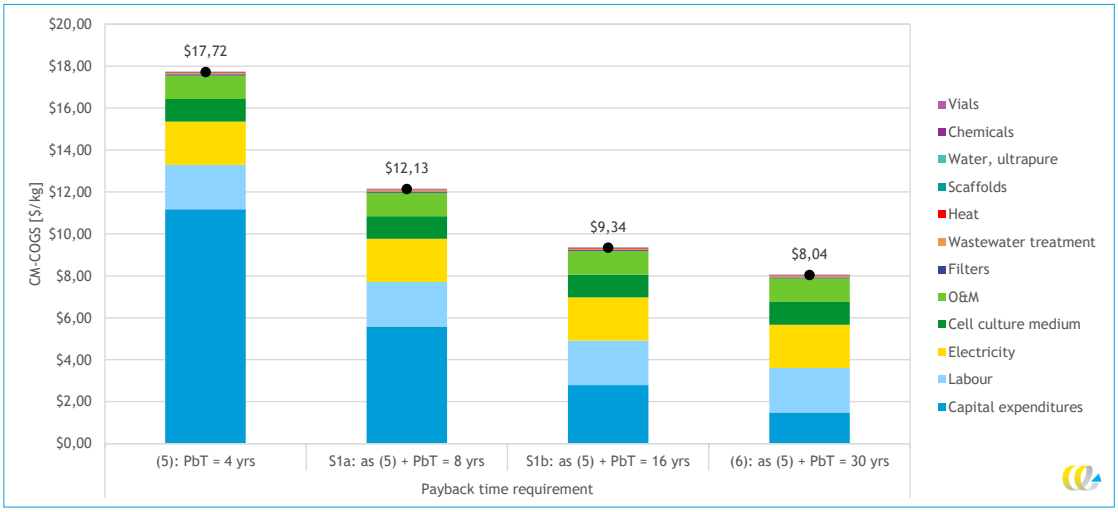
Maximum cell density during proliferation stages is a parameter for which many companies are optimising. The theoretical maximum cell density is highly dependent on the adopted product system and bioreactor types. In the stirred-tank reactor (STR) system that is modelled, $50*10^6$ cells/ml is the baseline cell density modelled. According to experts in the field, it may be feasible to increase cell densities in this system by a factor 4 (to $20*10^7$ cells/ml). However, this is also dependent on the volume of the cells, as in general not more than 25% of the reactor volume can be filled with cells (limiting volume fraction) (Humbird, 2020). Increasing cell densities at stable cell volumes therefore at a certain point crosses this limiting volume fraction threshold. With the baseline cell volume used in this study (3,500 μm^3), this threshold is reached at around $70*10^6$ cells/ml.

Higher cell densities would mean that more meat cells can be grown in a reactor of the same volume. It affects the energy demand for heating and cooling and the amount of proliferation reactors needed; higher densities mean that the same amount of CM can be produced in a smaller reactor volume, lowering investment costs. Also, less operators would be needed, lowering labour costs.

4.1 S1: Sensitivity for investment criterion

Below, we depict how sensitive CM costs are to the investment criterion used. In Section 3.2.3, we showed the impact of relaxing a commercial payback time requirement (4 years) to a social one (30 years). Below, add a COGS models for a payback time requirements that are 8 years and 16 years.

Figure 17 - Sensitivity for payback time requirement



Notes:

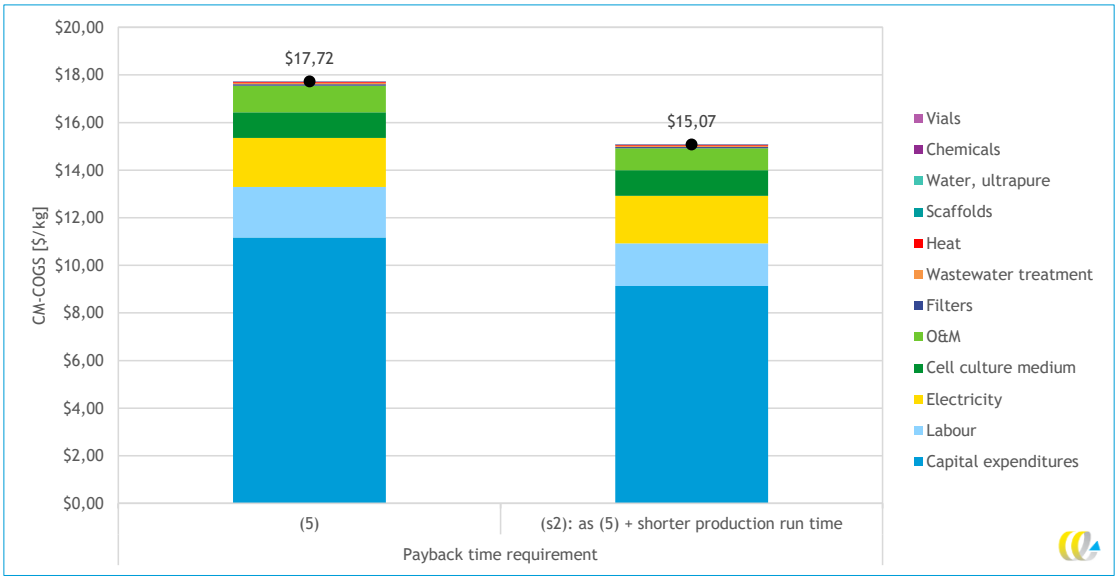
- Total yearly CAPEX are 110 mln (PbT = 4 years); 55 mln (PbT = 8 years); 22.5 mln (PbT = 16 years) and 15 mln (PbT = 30 years).

4.2 S2: Sensitivity for production run time

In this section, we add a shorter production run time on top of the scenario with a commercial investment criterion (payback time requirement = four years).

Shorter production run time in the reactors reduces overall energy demand, lowers medium demand during differentiation and maturation (we assume a linear relation) and results in a smaller amount of reactors needed to produce the same amount of CM.

Figure 18 - Sensitivity for production run time



Notes:

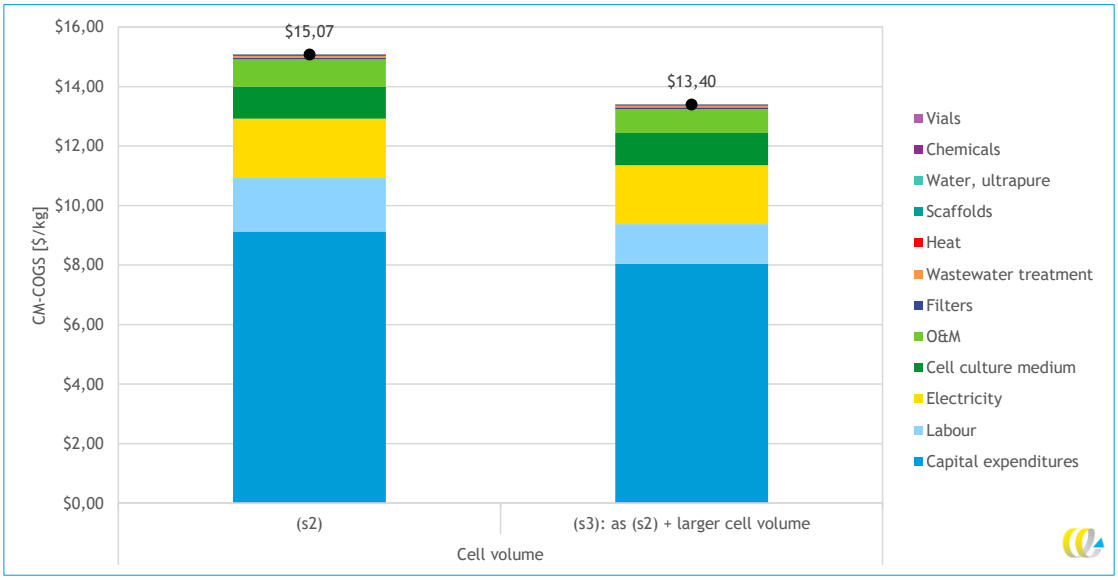
- Payback time requirement is 4 years in the sensitivity scenarios.
- (s2) equals (7), but with payback time requirement = 4 years.

4.3 S3: Sensitivity for cell volume

In this section, we add a larger cell volume on top of the shorter production run time. We retain a commercial investment criterion (payback time requirement = four years).

Larger cell volume means that less equipment is needed for the same production, as total cell mass harvested from one unit of volume decreases accordingly.

Figure 19 - Sensitivity for cell volume



Notes:

- Payback time requirement is 4 years in the sensitivity scenarios.
- (s3) equals (8), but with payback time requirement = 4 years.

From the COGS model above, we conclude that with a commercial investment criterion, CM production costs remain at a level of around $ 13. That is near the same order of magnitude as the benchmark production costs for conventional meat products ($ 2), but still substantially higher.

5 Conclusion and Discussion

In this report, we have analysed CM production costs at industrial scale. We have started with a COGS model based on current production technology and costs for inputs. We have then explored various avenues for cutting costs when production takes place in a full-scale plant that is realised in 2030.

We draw the following conclusions:

- **Current CM production costs** are an order of magnitude of 10,000 to 100 higher than benchmark values for comparable traditional meat products, depending on the exact requirements for medium components and its prices.
  In the basic scenarios of our study, we modelled a medium for which recombinant proteins, and then notably albumin, are the main cost driver, followed by growth factors. Our primary data shows a large variation in the use of these two components, which reflects potential opportunities for reducing these costs that depend on the type of production process used and the type of meat produced. Looking at the prices, we see that there are large variations in published prices. Also, we have observed that these prices are falling rapidly already, which is promising for the future.

- **Future CM production costs:** Substantial cost reductions that bring CM production costs close to the benchmark price for a traditional meat product are feasible. This requires a combination of reductions that covers nearly all aspects of the business case. We zoom into the following aspects:
  - Major steps need to be made in reducing the **production costs and use of medium ingredients**, notably growth factors but also recombinant proteins.
    Specht, (2020)discusses avenues to do this for growth factors drawing from similarities in producing enzymes like lipase, cellulose and amylase, produced at large scales through recombinant expression. With increased demand for certain growth factors their production could look more like current enzyme production, , allowing for production costs of around $ 4 per gram.
    For the recombinant proteins, we have industry sources that estimate production prices for these will fall below $ 1 per gram in 2030.
  - Furthermore, our assessment shows that the **requirements for return on investment** need to be set much lower than common practice in commercially motivated investments. Compared to traditional meat, CM production is capital intensive. This is reflected in high investment costs and high capital expenditures per kg CM produced. We have seen that if more socially motivated requirements for return of investment are adopted, capital expenditures may fall to a moderate amount. A more social investment criterion may be motivated by considerations of animal welfare or environmental footprint. These societal gains may also motivate governments to subsidise part of the investment costs. Finally, requirements for return on investment may also be lowered if investors allow for greater risk and in return get the opportunity to benefit from the learning curve in CM production technology.
  - Our assessment also shows that the **equipment costs for perfusion reactors** need to come down. Another avenue to bring capital expenditures down, is to reduce investment costs. Part of the technology used in CM-facilities are standard and no large cost reductions are to be expected. This applies to e.g. STRs and CIP/SIP system. However, the major part of investment costs is associated with the differentiation and maturation phase. In the production process modelled in this

research, the cells differentiate and mature in a perfusion reactor. Such a reactor has not yet been built for commercial production scales.
To obtain future cost reductions, computational models can inform best design practices as well as assist in the development of monitoring systems and control software. These new (perfusion or other) systems will need to be generalizable across a range of cultivated meat product types such that they can be mass-produced, resulting in affordability through production learning curves and economies of scale.

- **Improvements in the production process and favourable choices in cell types** will help drive down future costs. The primary data suggests there is quite some variation in envisioned production system design and specific process parameters. A few process parameters have come up as both variable and influential for production costs:
  - Total production run time influences overall energy demand, medium demand during differentiation and maturation and the amount of reactors needed at the facility. A shorter production run time can therefore lower costs substantially, but also yields a less mature final product, which in turn may influence its market value.
  - Average cell volume differs between species and cell types, and companies may want to consider selecting for large volume cells within species in order to lower costs. Larger cell volumes (at constant cell density) means that more meat cell mass can be produced from less reactors, in turn lowering investment and labour costs.
  - Finally it is important to strive for **maximum energy efficiency** of the production process. With all improvements mentioned above realised, electricity costs emerge as a major driver of total costs. This study takes a conservative approach towards heating and (especially) cooling energy consumption (for details see CE Delft, 2021). If companies see opportunity to achieve lower total energy demand, this will result in lower production costs.

- **Generate or invest in renewable electricity:** Another avenue for cost reduction that we have not explored quantitatively in this report, is the option to reduce electricity costs. Looking at Figure 14, we see that energy costs, and notably electricity costs, are the largest component in the COGS. This does not come as a surprise, because CM-production is indeed energy-intensive. However, it does raise the question if there are opportunities to bring these costs down, on top of the process efficiency improvements discussed above. We will discuss two avenues: the impact of location on electricity costs, and the impact of the type of generation of electricity.
  - Looking at location, it seems likely that there are differences in the costs for electricity generation that are associated with countries' differences in the costs of gas (and to a lesser extent coal) that are burned in conventional power plants. Depending on the development of cost reductions and subsidies for the generation of renewable energy, it may well be that in 2030 conventional energy production is the most expensive[17] and would drive the electricity market price. Currently, fossil fuel prices in the US are around a factor 2 lower than those in other parts of the world. It is likely that this cost advantage in the US will persist into the 2030's. This may translate itself into differences in the electricity price. So from the perspective of electricity price differentials CM is more likely to be competitive in the US market, than in the EU or Asian market[18].

[17] See e.g. WEO 2019 (IEA, 2019).

[18] Comparing e.g. China to US, indeed the difference in the costs of coal and gas is around a factor 2 (US cheaper), but this may be compensated by differences in the costs for staffing. If we compare EU to US, the US is factor 2 cheaper in energy and comparable in staffing.

- If we look at the type of generation of electricity, it seems likely that in the 2030's the price of electricity generated by solar PV and some other renewable sources undercut that of energy generated by gas or coal based power plants. For a CM-producer to benefit from lower costs of solar electricity, it may either generate the electricity itself (install solar panels on its terrain or roof of buildings), or invest in solar generation elsewhere. Examples of the latter are the Power Purchase Agreements (PPA). PPA's are long-term contracts that fix a price and amount of electricity purchases, that are closed between consortia that built renewable energy capacity and large electricity consuming companies such as for example railway companies. Given that electricity costs are such a large component of the COGS of CM, it may be worthwhile to explore this option.

Overlap TEA and LCA

At the same time this TEA was carried out, a life cycle assessment (LCA) was also made (CE Delft, 2020). Do conclusions overlap? Can measures to reduce environmental impact also lower costs, and vice versa? Four aspects stand out:

1. **Energy efficiency**: being more energy efficient reduces environmental impact and costs. There still are uncertainties regarding energy use for heating and cooling, and further research into e.g. energy efficient cooling and sustainable heat sources could help reduce both environmental impact and costs.

2. **Energy sources**: a switch to sustainable energy, especially electricity, substantially lowers the environmental impact. The most transparent and robust way to ensure *additional* sustainable electricity production, which actually lowers the national average environmental impact of electricity generation, is taking care of one's own sustainable electricity generation. If sustainable electricity is generated by the CM company on site, this could also mean a reduction in cost compared to either fossil or sustainable electricity purchased on the market.

3. **Medium use**: both increased medium efficiency and increasingly efficient production of ingredients can lower both costs and environmental impacts. Especially regarding certain functional ingredients: the results of the LCA and of the TEA both highlight certain specialty functional ingredients such as recombinant proteins in this regard. A reduction or a switch could mean reducing both impact and costs.

4. **Supply chain collaboration**: To reduce environmental impact and costs further, collaboration in the supply can help lower impact and costs of production of all required substances for CM production. Most notably this is important with regard to medium ingredients, but this reasoning can of course be extended to other inputs (e.g. scaffolds, filtration membranes) as well.

References

The references below are cited in this report. We refer to the LCA report (CE Delft, 2021) for additional references used for the models.

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A Inventory and data quality

The data quality assessment classification is explained in Table 4. Table 5 shows the main model design parameters with information on sources and data quality.
Table 6 shows the main model inputs with information on sources and data quality. Quantitative data on model inputs is confidential and therefore not included. Table 7 shows the conventional electricity mix modelled for this study. Table 8 shows the energy consumption modelled in the baseline model.

Table 4 - Data quality assessment classification

Data quality assessment classification	
0	No data available at this moment
1	Primary data from representative process and scale
2	Primary data from representative process with extrapolation for scale
3	Primary data from similar process and scale
4	Secondary data from literature
(5	Estimate or calculation based on expert judgement

Table 5 - Main model design parameters values, sources and data quality

Main model parameters	Value	Source	Data quality	# of data points used	Independent crosscheck
Annual production of commercial facility in 2030	10 kton	CM and supply chain companies	5	12	No
Species and cell type	Various, all non-GMO cell lines	CM companies	1	7	Yes
Type of production	Semi-continuous production with 3 intermediate harvests	Literature, confirmed by bioprocessing companies	4	1	Yes
Size of largest proliferation vessel	10,000 L	CM and supply chain companies estimate (median)	5	7	Yes
Size and amount of bioreactors at facility	130 x 10,000 L STR; 4,300 x 2,000 L PR	Calculated, based on production line presented in Specht and project-specific parameters	4/5	-	No
Doubling time	30 hours	Conservative round-up from Specht : 28 days	4	1	No
Duration of production from inoculum to harvest	42 days (30 days for ~25 doublings + 2 days for additional harvests + 10 days of differentiation and maturation)	Specht , crosscheck by bioprocessing companies	4	1	Yes

Main model parameters	Value	Source	Data quality	# of data points used	Independent crosscheck
Maximum cell density	50*10^6 cells/ml	CM and supply chain companies (median)	2	7	No
Avg. cell volume	3,500 μm^3/cell	CM companies	1	4	Yes
Density of meat	881 kg/m^3	Specht	1	N.a.	No

Table 6 - Main model inputs, sources and data quality

Main model inputs and their production	Source	Data quality	# of data points used	Independent crosscheck
Energy use for production (heating, cooling, mixing, aeration, pumping)	Calculations by bioprocess engineers with extrapolations by CE Delft.	5	1	Yes
Energy use for cleaning (CIP/SIP)	Calculations by bioprocess engineers with extrapolations by CE Delft.	3	1	No
Energy use for HVAC	Calculations by bioprocess engineers.	4	1	No
Energy production	Ecoinvent LCA database, modelled after global stated policies scenarios 2030 in World Energy Outlook (IEA, 2019)	1	N.a.	N.a.
Purified water use for CM production	CM and bioprocess engineering companies.	2 (for medium-related water use) and 3 (for cleaning-related water use)	2	Yes
Purified water production	Water companies.	1	1	No
Medium use	CM and supply chain companies.	2	6	Yes
Medium recycling rate	CM and supply chain companies.	0 (no consensus)	6	Yes
Medium composition	CM and supply chain companies.	2	7	Yes
Medium ingredient production	See below.			
Hydrolysate	(Colantoni et al., 2017) EDIT: Soy LUC set to 0 (as is done for conventional products).	4	1	No
Amino acids	Data from (Marinussen & Kool, 2010), Mattick (2014), Mattick et al. (2015). Amino acids modelled: L-Glutamine, L-Threonine, L-Lysine, D,L-Methionine	4	1	No

Main model inputs and their production	Source	Data quality	# of data points used	Independent crosscheck
Recombinant proteins	Amino acid production data from (Marinussen & Kool, 2010), Mattick (2014), Mattick et al. (2015) used as basis. Water and electricity use adapted for recombinant protein fermentation with data from 2 producing companies.	2	3	Yes
Other medium ingredients	Ecoinvent and Agri-footpint LCA databases.	1	N.a.	N.a.
Transport of medium ingredients	Based on standard Ecoinvent values for global markets.	1	N.a.	N.a.
Scaffold use	CM and supply chain companies.	5	8 companies (total) of which 3 with future estimate of quantity of scaffold used	No
Scaffold production	See below.			
Hydrogel	De Marco et al. (2017).	4	1	No
Electrospinning	Supply chain companies.	2	2	Yes
Bioreactor use	Size from CM and supplying companies, amount calculated.	See above	See above	Yes
Bioreactor production	Tuomisto et al., (2014) and industry experts within CE Delft.	4	2	Yes
Storage and mixing tanks use	Calculated.	5	1	No
Storage and mixing tanks production	Industry experts within CE Delft.	4	1	No
Filters for filtration use	Supplying companies.	2	1	Yes
Filters for filtration production	Supplying companies.	1	1	No

Table 7 - Energy mix for 2030, stated policy scenario, global average

Source	Share
Coal	29%
Gas	24%
Oil	3%
Nuclear	9%
Hydro	15%
Wind	9%
Solar	9%
Other renewable	3%

Table 8 - Modelled energy demand for one year of operation (baseline scenario)

Process	Quantity (kWh)
Electricity for aeration, agitation, pumping and heat exchanger during small-scale proliferation, large-scale proliferation and differentiation and maturation; centrifugation and pumping washing water during harvesting and as part of food safety measures; pumping during cleaning; HVAC; pumping (medium mixing and sterilisation.	2,17E+08
Heat for initial heating of medium during small-scale proliferation, large-scale proliferation and differentiation and maturation and cleaning; HVAC.	1,08E+07

B Medium formulation and prices

B.1 Medium formulation and prices per ingredient category

Table 9 - High-medium

Ingredient	Weight g/kg CM	Prices $/kg ingredient	Total costs $/kg CM
Amino acids (total)	400.0	15.13	6.05
Amino acids from hydrolysate	300.0	3.50	1.05
Amino acids from conventional production	100.0	50.00	5.00
Sugars (total)	400.0	25.53	0.68
Sugars: Glucose	396.0	0.70	0.28
Sugars: Pyruvate	4.0	100.00	0.40
Recombinant proteins	50.0	400,000.00	20,000.00
Salts	160.0	2.10	0.34
Buffering agent	100.0	55.00	5.50
Vitamins	20.0	60.00	1.20
Growth factors	0.001	2,391,176,470.59	2,391.18
Water	40,000.0	0.01	0.40
			Total:
Total (g)	41,130.00		22,405
Total (L)	41.7		

Table 10 - Mid-medium

Ingredient	Weight g/kg CM	Prices $/kg ingredient	Total costs $/kg CM
Amino acids (total)	316.2	4.78	1.51
Amino acids from hydrolysate	237.2	2.65	0.63
Amino acids from conventional production	79.1	11.18	0.88
Sugars (total)	77.5	2.91	0.06
Sugars: Glucose	75.5	0.53	0.04
Sugars: Pyruvate	2.0	10.00	0.02
Recombinant proteins	7.1	198,919.58	1,406.57
Salts	80.0	0.46	0.04
Buffering agent	31.6	35.57	1.12
Vitamins	2.0	20.49	0.04
Growth factors	0.000	890,151,808.52	281.49
Water	12,649.1	0.01	0.13
			Total:
Total (g)	13,163.49		1,691
Total (L)	13.4		

Table 11 - Low-medium

Ingredient	Weight g/kg CM	Prices $/kg ingredient	Total costs $/kg CM
Amino acids (total)	250.0	2.13	0.53
Amino acids from hydrolysate	187.5	2.00	0.38
Amino acids from conventional production	62.5	2.50	0.16
Sugars (total)	15.0	0.55	0.01
Sugars: Glucose	14.0	0.41	0.01
Sugars: Pyruvate	1.0	1.00	0.00
Recombinant proteins	1.0	98,922.50	98.92
Salts	40.0	0.10	0.00
Buffering agent	10.0	23.00	0.23
Vitamins	0.2	7.00	0.00
Growth factors	0.000	331,372,549.02	33.14
Water	7,500.0	0.01	0.08
			Total:
Total (g)	7,816.20		133
Total (L)	8.0		

B.2 Sources of prices

Components	Prices ($/kg)		Source
	Low	High	
Amino acids (total)			
Amino acids from hydrolysate	2.00[19]	3.50	(Humbird, 2020)
Amino acids from conventional production	2.50	50	Specht
Sugars (total)			
Sugars: Glucose	0.41	0.70	Alibaba[20]
Sugars: Pyruvate	1	100	Alibaba[21]
Recombinant proteins	98,923	400,000	Invitria[22], [23], Northwestern Medicine[24] & Specht (2020)
Salts	0.10	2.10	Specht (2020)
Buffering agent	23	55	Specht (2020) and Alibaba
Vitamins	7	60	Specht
Growth factors	331,372,549	2,391,176,471	FGF-b: Orf genetics[25]; TGF-b§: Qkine[26] and Specht (2020)
Water	0.01	0.02	Quote from industry

Note: Mid-price is calculated as the geometric mean of low and high price.

[19] Price in the original study (0.4 $/lkg) was based on agricultural grade hydrolysate. In the corrigendum, the price is based on food grade hydrolisate (2 $/kg).

[20] Alibaba: Glucose Syrup,Liquid Glucose

[21] Alibaba: Best price Pyruvic acid CAS 127-17-3

[22] InVitria Products : Cellastim S

[23] InVitria products : Optiferrin® Recombinant human transferrin

[24] Feinberg School of Medicine, Paul Burridge Lab : B8 index

[25] ORF Genetics product : MESOkine - FGF-basic

[26] Qkine product : recombinant human tgf b1 plus protein

C Investment costs and fte

Plant design Equipment type	Pieces of Equipment/ fte staff	Equipment costs		Installation factor	Total costs (mln $)
		$/piece	Equipment purchase costs (mln $)		
Perfusion reactor 2,000 l	430	600,000	152	NA	260
STR 10,000 l	130	325,000	24	3.5	150
STR 50 l	107	90,000	4	2.2	20
Storage and mixing tank 60,000 l	15	175,000	3	3.5	10
CIP/SIP			3.5	2.2	7.5
Total					450
Staff	200				
Maintenance	~5% of bare equipment costs				

Notes:

- Source: calculations by CE Delft based on conversations with industry experts.
- Equipment costs based on agitated equipment including basic instrumentation.
- Installation factors represent industry benchmarks for individual equipment installation costs including placement, instrumentation, piping, electrical, buildings, engineering and contractors. The factors shown are representative of industrial biotechnology (including food) and when combined, represent an overall Lang Factor of around 3, indicating the equipment purchase cost represents about one third of total project costs (Warner Advisors LCC).
- We assume that STR 50 liter are bought as a package, so partly pre-installed.
- CIP is a skid-based system.
- Costs for perfusion reactor is based on a benchmark index number, and includes installation costs.
- Values for STR's, storage and mixing tank and CIP/SIP should be considered FEL-1, hence an uncertainty bandwidth of unit costs of -20% to +40%. but prices are conditional on development of steel prices towards 2030. Values for perfusion reactor have a larger uncertainty bandwidth.
- Staffing estimate assumes 24/7 operation in shifts and includes operators, lab, managers, small maintenance (Filters, O-rings, etc.). This is based on considerations for capacity and amount of reactors.
- Maintenance excludes small maintenance (filters, O-rings, etc.)

D Other costs and prices

Input	Source	Unit	Value	Source
Electricity	a: mix electricity	$/kWh	0.095	Calculations by CE Delft based on PBL, CBS, TNO and RIVM, and data from statistics Netherlands.
Electricity	d: mix wind/PV	$/kWh	0.084	Calculations by CE Delft based on Irena (2018, 2020), PBL, CBS, TNO and RIVM, and data from statistics Netherlands.
Heat	a: gas	$/kWh	0.035	Calculations by CE Delft based on IEA (2019), PBL, CBS, TNO and RIVM, and data from statistics Netherlands.
Heat	d: geothermal heat	$/kWh	0.083	Calculations by CE Delft based on PBL and data from Statistics Netherlands.
Liquid nitrogen		$/m^3	0.327	Calculations by CE Delft based on quote from supplier.
Vials		$/piece	0.036	Calculations by CE Delft based on quote from supplier.
Sterilization filters[27]		$/piece	225	Calculations by CE Delft based on quote from supplier.
Chemicals		$/kg	0.30	Alibaba.com, prices for NaOH.
Water, ultrapure		$/l	0.0014	Value form industry.
Labour		$/fte	100,00	Value from industry.
Scaffolds	Hydrogel (not electrospun)	$/ton	135	Data from various experts.

[27] Please note that 90% of the medium is heat-sterilised and the remaining medium (with concentrated heat-sensitive substances) is sterilised using sterilization-grade filters.

E Cost components excluded from the analysis

The following components are not included in the analysis:

- centrifuge for recycling media;
- cell banking system;
- air (elevated concentration of CO_2).

F Model inputs for Scenarios 7-8

Table 12 - Parameters and the relative change in parameters for the different sensitivity analyses

Parameters changed	Baseline scenario (mid medium)	A1 Shorter production run time (-25%: 32 days, 3 harvests)	C2 Larger cell volume (5,000 um^3)	D1 Low medium[e]	D2 High medium[e]
Amount of production runs[a]	100%	100%	70%	100%	100%
Amount of bioreactors (50 L STR)	100%	79%	70%	100%	100%
Amount of bioreactors (10,000 L STR)	100%	85%	69%	100%	100%
Amount of bioreactors (2,000 L PR)	100%	79%	100%	100%	100%
Amount of storage and mixing tanks (60,000 L)	100%	100%	100%	100%	118%
Electricity for small-scale proliferation (total)[b]	100%	99%	99%	100%	100%
Heat for small-scale proliferation (total)[c]	100%	100%	100%	51%	356%
Electricity for large-scale proliferation (total)[b]	100%	99%	99%	100%	100%
Heat for large-scale proliferation (total)[c]	100%	100%	100%	67%	271%
Electricity for differentiation and maturation (total)[b]	100%	75%	100%	100%	100%
Heat for differentiation and maturation (total)[c]	100%	75%	100%	39%	418%
Electricity for cleaning (pumping)	100%	100%	70%	100%	100%
Heat for cleaning (heating water)	100%	100%	73%	100%	100%
Electricity for medium mixing and sterilisation (kWh)	100%	100%	100%	59%	311%
Electricity for HVAC (total)[d]	100%	100%	100%	100%	150%
Heat for HVAC (total)[d]	100%	100%	100%	100%	150%
Water for cleaning	100%	100%	82%	100%	100%
Medium (small-scale proliferation)[e]	100%	100%	100%		
Medium (large-scale proliferation)[e]	100%	100%	100%		
Medium (differentiation and maturation)[e]	100%	75%	100%	see Table 11	see Table 9

[a] One production run consists of a train of proliferation reactors of increasing volume and 4 perfusion reactors (see Section 2.3). Depending on the potential staggering of production runs this is more or less proportional to the total amount of reactors needed for the facility.

[b] Electricity for the various production stages includes all aspects that are powered by electricity: Pumping, mixing, aeration and cooling in a heat exchanger.

[c] Heat for the various production stages is the heat needed for initial heating of the medium.

[d] HVAC includes all heating, cooling and ventilation needed to maintain ISO8 environment in the production area, as modelled in the LCA-report. This standard is more conservative then strictly required according to the 'food grade' assumption for the production environment. As HVAC-costs constitutes 0,1% of total costs, this remains unchanged in the corrigendum.

[e] All scenarios except low- and high-medium assume the baseline medium quantities. For the low- and high-medium scenarios, see Annex B.