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Sustainability in the beverage industrial sector:

decarbonisation of a Scotch whisky distillery

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Abstract

The importance of sustainability is nowadays well known worldwide and taken in consideration in every aspect of people's lives. In this context, since energetically speaking industry is one of the most consuming and thus pollutant fields, the scope of this study is to analyse the beverage industrial sector, in order to individuate the options for a decarbonisation of facilities in this area. At first, a brief description of production processes of some alcoholic and non-alcoholic beverages is made: soft drinks, brandy and whisky manufacturing are presented. Then, focusing on a Scotch whisky distillery, a variety of decarbonisation options that are applicable to each step of the whole production chain are listed and explained. Considering that one promising option is represented by anaerobic digestion of by-products, with consequent production of biogas, the energetic potential of waste materials resulting from the three aforementioned beverages production is investigated in this sense. In the following part, an overview of different kinds of energy system models is carried on, concentrating on how the industrial sector can be modelled through each one of them. Among this list, the simulation software HOMER Pro was chosen to model a Scotch whisky distillery energy system, that was taken as a case study. Within the model, different configurations with renewable energy sources such as photovoltaic and biogas are considered in order to identify the best solution for the decarbonisation of the plant.

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Introduction

There's no need anymore to highlight the importance of sustainability and related actions to take for climate change opposition. In particular in the energy field, decarbonisation is an essential practice to be carried out. Industry is responsible for almost one third of the total global CO_2 emissions, considering both direct industrial processes, but especially energy use in industry, that is where the biggest part of energy is employed in the world. Food & beverage sector is the third highest consumer of energy in industry, although it has less impact than iron & steel or chemical & petrochemical, that are respectively first and second ones. [1] The same scenario is present in UK, where food & drink follows iron & steel, chemical & oil refining in the list of major energy consumers and CO_2 emitters, with its 9,5 million tonnes of CO_2, accounting for 11,7% of total national emissions [2]. Staying in the UK borders, food & beverage is considered the largest manufacturing sector [3], with 15% of manufacturing turnover and employment and a continuous growth since 1994 until recent years [4]. Here, the beverage sector is divided as in Figure 1 [4], with beer being the drink with highest value, but immediately followed by soft drinks, wine and spirits.

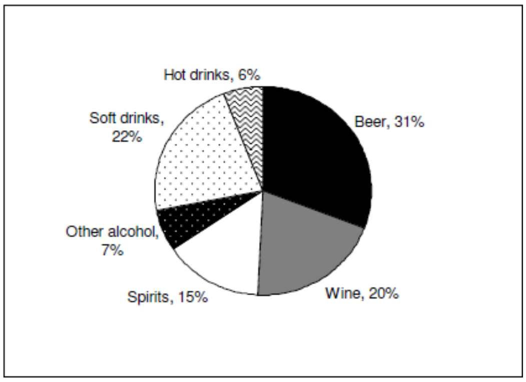

Figure 1 – UK drinks distribution

Among all the beverage types, alcoholic ones represent 1,46% of total Greenhouse gases emissions, formed for 0,96% by beer, 0,4% by wine and 0,1% by spirits [3]. Figure 2 shows the subdivision of UK market between main alcoholic drinks categories, while Figure 3 divides spirits sales into single products [4]. The most famous and diffused spirits in the world can be considered whisky (about 65% of global production) and vodka (about 20%), followed by tequila, cordials, rum, brandy, cognac, gin, pre-mixed cocktails in no particular order. [5]

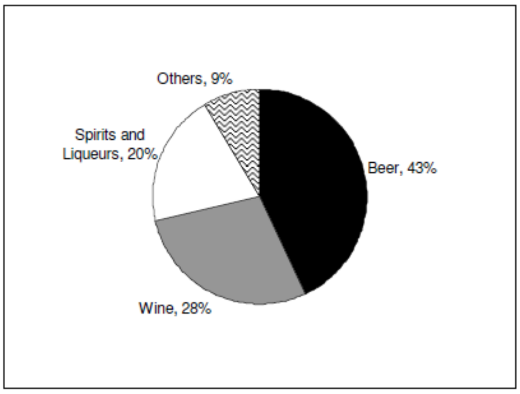

Figure 2 – UK alcoholic drinks sales

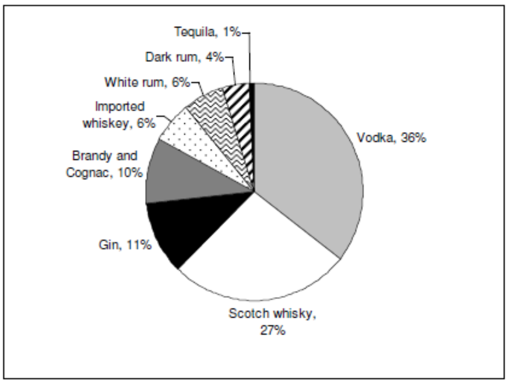

Figure 3 – UK spirits sales

Taking a look at the USA spirits market, the top products are, in order, whiskey, vodka, tequila and rum, and they all had +15,2% increasing sales in the last year with respect to prior year [6]. Considering the top 20 among US generic beverage companies and foreign companies with significant sales in US, 8 of them produce spirits, while 5 soft drinks producers fall within the top 10 [7]. More generally, the top 50 companies that distil, blend or mix liquors account for the 90% of the whole sector income in the world [5]. Focusing on whisky industry only, in 2021 world trade rose of 17,8% with respect to 2020, calculated in USD [8]. India is the major whiskey producing country [9], although the origins of this beverage make it immediately associated to United Kingdom. In all the territories of UK, Scotch whisky represents the 87% of alcohol production [3] and 25% of total food & drink exports. Scotch whisky play an important role in the British industry, employing more than 10.000 people and accounting for 0,6% of food & drink national greenhouse gases emissions, summing up whisky production and its home consumption. [4]

Chapter 1 – Food and beverage

Production processes of some beverages

Soft drinks

Among all the beverages sold worldwide, non-alcoholic drinks share is one of the bigger, considering carbonated drinks, fruit juices, iced tea, coffee and bottled water altogether. Soft drinks production, in particular, consists of purifying water, mixing it with sweeteners, flavours and other liquid or solid additives, adding carbon dioxide (stored in liquid phase) and then bottling or canning (see Figure 4). During the entire process (including bottle washing, product filling, heating or cooling and cleaning-in-place (CIP) systems, beverage manufacturing, sanitizing floors, cleaning of zones and piping networks), a lot of water is consumed (about 2.5-3.0 litres per each litre of drink produced), being bottle washing the most water-consumer, with 1.25 litres wasted per litre produced. Other non-alcoholic beverage process may differ slightly, but in any case there is a huge consumption of water, that reflects in a big amount of wastewater produced, that cannot be directly discharged into the environment because of the presence of a variety of pollutants in it. [10]

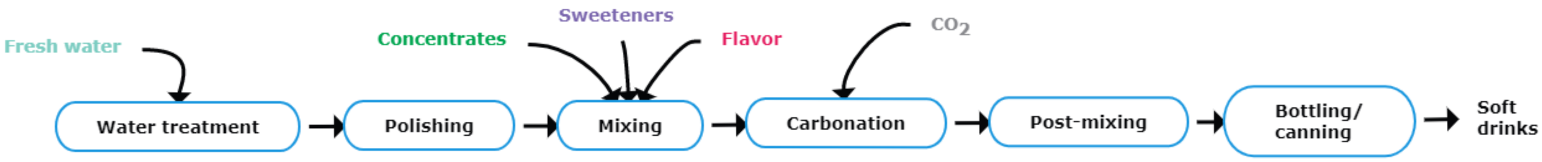

Figure 4 – soft drinks production process

Alcoholic beverages

Alcoholic beverages can be very variegated depending on their raw materials, production methods and final taste. The biggest family is the one of spirits (also called liquors in USA and Canada), that are obtained by distillation of fruit, cereals, vegetables, botanical herbs containing sugar, and then can be drank as they are or with adding of flavours, such as fruits, herbs or spices, that makes them turn into liqueurs. The word *distillation* derives from Latin *destillare*, that means to drop down, since this technique consists in condensing alcohol vapours after boiling. Historically, it was probably invented in Mesopotamia 5.500 years ago by unknown priests or craftsmen and known since ancient times in Asia (China, Japan, India, Mongolia). Arabs imported this kind of knowledge to Europe from the south, in the Early Middle Ages, when it was used for alcoholic beverages, medical products and perfumes [11]. The first written evidence about distillation was around 1310 by Arnaud de Villeneuve [12]. Distillation method involves the separation of constituent elements (mainly water and alcohol) by profiting by their different levels of relative volatility. In the vapour obtained by boiling a liquid there are higher amounts of volatile compounds, so that the condensate liquid will be richer in them than the first one. The higher number of times distillation is repeated, the higher the volatile components concentration will be. [12] Specifically, in distillation for alcoholic beverage production, the difference in evaporation temperature of water (100°C) and alcohol (78°C) is exploited.

As already mentioned, distilled beverages are called spirits, but a more precise classification can be made. Neutral spirits, also called white spirits or non-aged spirits, necessitate removal of every compound that contains or gives odour or taste. Specifications indicate quantity of congeners allowed, that can be even less than 1 ppm, thus a double, triple or quadruple rectification (that means 2, 3 or 4 distillation columns) is needed, depending on the required purity grade. The most famous examples of neutral spirits are gin and vodka. On the other hand there are the so-called brown spirits, because maturation in wooden casks gives them a brownish aspect. They can be divided into feedstock-influenced flavoured spirits, as whiskey, rum, brandy, tequila and Italian grappa are, and highly rectified spirits, that are lighter in colour and taste, such as Canadian rye whiskies, light American whiskeys and light rums. [13], [14]

Brandy

Liquors produced from wine are generally known as brandy, but the name can vary depending on the region where it is produced (the most famous and finest worldwide is maybe Cognac, that is produced in the French region of Charente and some surrounding territories).

Brandy production process starts in the very same way as the white wine production, with the crushing of grape and its fermentation, during which fruit sugars are transformed into alcohol and carbon dioxide. So far wine and brandy have in common not only the production process, but also waste is the same: it is grape marc (also called grape pomace or vinasse), composed by seeds, skins, stalks and pulp in different proportions [15]. Then wine is moved into copper pot stills, where it is heated (usually with gas as source) in order to be distilled once or several times, according to the quantity of alcohol looked for. Thanks to a lower boiling temperature with respect to water, alcohol evaporates and when its vapour is cooled, it condensates again. Alcoholic liquid is at this point collected and stored into oak barrels for a long time, that can be from 2 years to whole decades: aging determines shades of colour and taste, as well as price naturally.[16] Figure 5 outlines the main stages of brandy production.

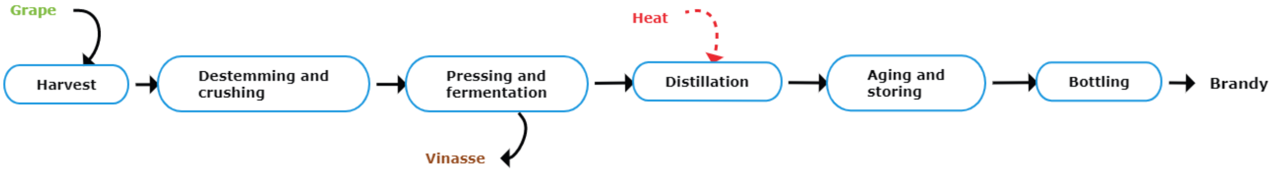

Figure 5 – brandy production process

Whisky

History

Another alcoholic drink that is worldwide produced and consumed is whiskey. Whiskey can be a useful source, as etymology of the word suggests: it comes from the Gaelic "*uisce beatha*" that means "water of life" [17]. The same meaning is assumed by distilled spirits in general, where Latin word *aquavitae* is at the base of modern languages such as French, Italian, or some Northern Europe idioms [12].

First whisky may have been produced in Ireland and then exported to Scotland (specifically on Islay Island and Speyside) by the English monks. In 16th century it was used as a medicine and in 17th century the first taxation on production was introduced: it was 2 shillings and 8 pence on each pint (about 1,5 litres). Then it was transformed into a tax on malt and finally abolished. From 1751 on, a series of acts put more and more taxation upon Scotland's whisky production: as a consequence illegal distillation started.

In order to have a clear distinction between different kind of whiskeys from around the world, an overview of main types of whiskeys with a little description is reported in Table 1 [9]:

Malt whisky	Only malted barley. Continuous distillation prohibited in 2009. “Single” means that all the whiskies in the bottle were produced within the same distillery. Handcrafted
Grain whisky	It can be made of any type of grain or a mixture of them (e.g. wheat, corn…). Usually distilled in column stills (cheaper than pot stills) and used to be blended with malt whisky. It has shorter maturation times. Industrially produced
Blended whisky	Mixture of any kind of whisky (usually grain and malt), coming from different distilleries, each one producing its unique character. Typically from Scotland and Ireland
Pot still whisky	Like a blended whisky (malt and grain), but both distilled in pot stills. It can be single if both were produced in the same distillery. Produced in Ireland.
Bourbon	Whiskey produced anywhere in the USA, made by at least 51% corn and the rest by barley, rye and/or wheat, mainly column-distilled. Aging of at least 2 years in new toasted American white oak casks. Straight means not blended
Tennessee whiskey	Bourbon that has been mellowed: filtered through charcoal before aging
Rye whiskey	At least 51% rye. Produced in USA but now mainly in Canada. Used for blending
Corn whiskey	100% corn made, in the USA. Used for blending, since it has quite neutral taste

Table 1 – types of whiskeys

Scotch whisky production

Scotch whisky is a particular type of whiskey, that has to be made in Scotland with malted barley only (while whiskey produced elsewhere can employ other grains like corn, rye or wheat). It can be *straight malt whisky* (barley only) or be blended with *Scotch grain whisky* (also called *patent-still whisky*), usually in a proportion of 20÷30% malt and 70÷80% grain; in a blend there may be up to 20 or 30 different whiskies mixed. In order to carry the label of *Scotch whisky,* it has to follow some strict legal rules that were defined by Scotch Whisky Order (1990) and Scotch Whisky Act (1988) [12], [18]:

- It is made with water, malted barley and only whole grains or other cereals
- Processing, malting and fermentation must take place at a distillery in Scotland
- Mashing must be done in the same distillery
- Only endogenous (natural) enzymes can be used for conversion of starch to sugars
- Only yeast used for fermentation
- Distillation produces an alcoholic strength by volume of less than 94,8%
- The colour, aroma and taste of the raw materials are preserved during production and maturation
- Maturation takes place in Scotland (in oak casks with a capacity not to exceed 700 litres) and lasts at least 3 years
- No additional substances be added other than water and plain caramel colouring (E150A)
- The final bottled product has a minimum alcoholic strength by volume of 40%

Scotch production process is outlined in Figure 6. Basic ingredients are barley (species of *hordeum vulgare L.* or *hordeum distichon)* and water. Scotland has very soft water, with no limestone, that each distillery extracts from wells in the surroundings. Barley can either be grown in Scotland or imported from England, continental Europe or even Canada, since Scottish barley only wouldn’t be enough for the entire Scotch whisky production. Summer barley, that has higher starch content later converting into fermentable sugar, is more used for whisky production than winter barley, richer in proteins and nitrogen, that give whisky bitterness. From 100 kg of barley, around 30÷32 litres of pure alcohol are extracted [19]. Barley is at first mixed with warm water in malting step, when it is let germinate on a malting floor until the germ has reached about two thirds of grain's length and the starch molecules are split into smaller particles. Wet barley is distributed upon multi-layered grids in the kiln, a furnace covered by the traditionally characteristic pagoda roof, where hot air from below dries the malt until it has a humidity of about 4%. Peat can be added to the fire with the aim of giving malt a smoky hint. Kiln temperature can't exceed 55°C since enzymes in the grain must be preserved, so a good ventilation is important: that's the reason why pagoda roofs, that cover the chimney preventing rain entering, were built since 1889, according to the Asian style. Modern distilleries have no longer pagodas, unless for decorative purposes: indeed majority of distilleries carry out malting in a different site. Malt is then grinded by a mill into a coarse flour called grist (the right granularity is important for complete sugar extraction), and mixed three times with hot water (respectively at 65°C, 80°C and 95°C, where sugar solution is recovered for the first step), forming what is called *mash* and the mixture is stirred until soluble sugars are extracted thanks to enzymes in the malt, that catalyse the hydrolysis of starch. Finally mash is cooled down to 20°C: solid leftovers here produced are called *draff*. Yeast (strains of *saccharomyces cerevisiae*) is added in the proportion of 10 grams per 30 litres of solution, forming the so-called *wort*. Wort is left to ferment into the washback (wooden or stainless steel covered tank with foam removing blades) for 2 to 4 days, where yeast converts sugars into alcohol and carbon dioxide, that can be collected and sold for subsequent industrial use. The resulting fermented liquid with 8÷9% alcohol is called *wash* (or *beer*). Then the alcoholic liquid goes through a first distillation in one of the traditional onion-shaped copper stills of 20.000÷30.000 litres (this one is called *wash still*): alcohol steam passes through neck of the still and lyne arm (conical duct) and goes into a condenser. The pot stills were traditionally heated by direct flame (first by coal, then by gas) while now heat is given by internal coils full of steam, which must be always under the level of fluid to avoid burning of solid particles on the external surface of the coils. In addition, temperature must be controlled since if it was too high, a lot of substances like fusel oils would be dragged into the whisky, giving it a rough taste. After boiling for 5 to 6 hours, wash divides itself into *pot ale* (liquid waste) and *low wines*, which are a very rough liquid with 20 to 25% alcohol, so it is transferred into the *spirit still* (or *low wines still*) of 10.000 to 20.000 litres, where second distillation takes place in a range of 4 to 8 hours. Chronologically first (*foreshots*) and last (*feints* or *tails*) liquids here extracted are respectively too high and too low in alcohol content and they both have an unpleasant taste. due to substances such as acetone, fatty acids and heavy oils, so they are discarded. Moreover, foreshots may contain methanol, that is poisonous and potentially lethal, even if modern yeast strains prevent its formation, while feints contain fusel oils, causing headaches. The *heart*, that is distilled in the middle, instead, is the pursued one, with a specific alcohol content between 63 and 70% in volume. The still end is sealed by government for taxes applying. Checking is possible only visually and by means of measurement instruments (e.g. hydrometers) through the safe: a transparent box where part of the flow is diverted and then returned to production chain by valves and levers operated by a stillman. This is also the way he selects the middle cut (produced during 3 hours) and identifies it among foreshots (30 minutes) and feints (recirculated to spirit still). In modern plants automated systems measure temperature, that is strictly related to alcohol quantity, to indicate when switching from collection to discharge of distillate. Waste material remaining after the second distillation, called *spent lees*, is removed from the bottom of the still. In small distilleries a pipeline moves whisky from the spirit receiver directly into the casks, while in bigger facilities there is an intermediate collecting tank (where different production batches are mixed together and thus homogenized) and a separate pumping system. Whisky is diluted with treated water (softened or demineralised for a clearer aspect of liquid) up to desired alcoholic strength. Then oak casks are filled, mostly handmade, through the hole on the side of the barrels, that is then sealed with a cork. Each cask has to be labelled with an identification number, the name of distillery and production year. Usually whisky is matured into reused casks, that were previously used for bourbon or sherry, for example.

Oak wood is used because it is breathable and long-lasting, but different types of oak give different flavours. New casks are charred before use. Table 2 contains a list of different cask sizes:

Size name	Capacity [litres]
Quarter cask	125
Barrel	158
ASB (American standard barrel)	200
Hogshead	238
Butt	500
Puncheon	320
Pipe	700

Table 2 – casks sizes

After weighing the full casks for taxes estimation, they are moved to the warehouse for maturation, where they are stored for a legal minimum of 3 years and 1 day before it can be properly called *Scotch*, but normally they are aged for more time, up to 18 years or even more [12], [20]. During maturation time, part of the liquid is lost: this is called angels' share and it accounts for 6 to 40 % of total volume, approximately 0,2÷0,6% of alcohol per year. This is due to evaporation of both water and alcohol in a different ratio, that is strongly dependent on warehouse environmental conditions, mainly temperature and humidity influenced by local climate and construction type of the warehouse itself, and on casks properties such as size (because of surface/volume ratio), fill strength and position inside the warehouse. Low temperature and high humidity of Scotland weather make alcohol evaporate more than water, resulting in an aged whisky with a lower alcohol content than it was immediately after distillation. Warehouse conditions have an impact also on flavour development, together with casks properties such as wood type, charring depth of inner surface, cooperage techniques and the number of times they were filled [14]. Experts analyse smell and taste of samples of whisky and recommend producers on how to blend and mix large quantities of whisky, striving to keep the same quality of a product over the years. Although whiskies combined are from different casks and different years, if they were all produced in the same distillery, the resulting product is still called Single Malt. The year indication refers to the youngest whisky in the blend. An extra dilution with water may occur after blending, and then the spirit is stored for further time into reused casks for the so-called *marrying*. Colouring is made through adding caramel in order to reach the desired shade of brown (that can't be reached with coloration released by cask wood only). The final step before bottling is filtration through cellulose sheets with the purpose of a clearer whisky (chill filtration can be done to prevent additional later forming of haze, by removing tannin). Majority of distilleries don't have their own bottling plant, but they deliver casks to bigger specialised industries. Glass bottles are washed, before being filled, with the same whisky they're going to contain. After filling, bottles are closed with corks, sealed (e.g. with capsules), labelled and finally collected in stocks for shipping. [12], [20]

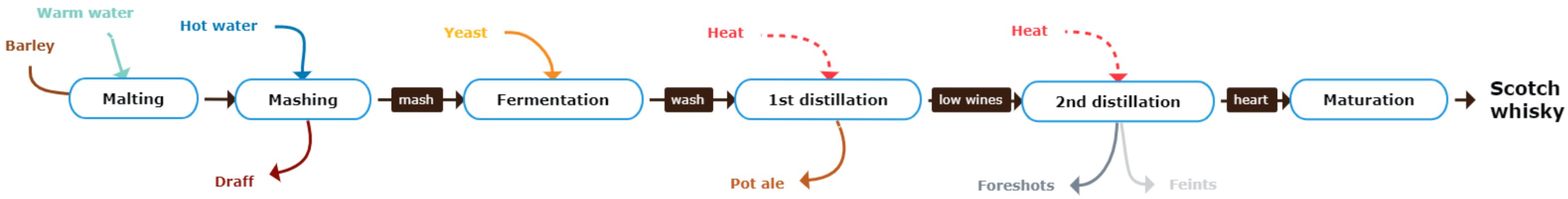

Figure 6 – Scotch whisky production process

Figure 7 shows main stages of Scotch malt whisky production, with a flow diagram of materials and some of the components in use [12].

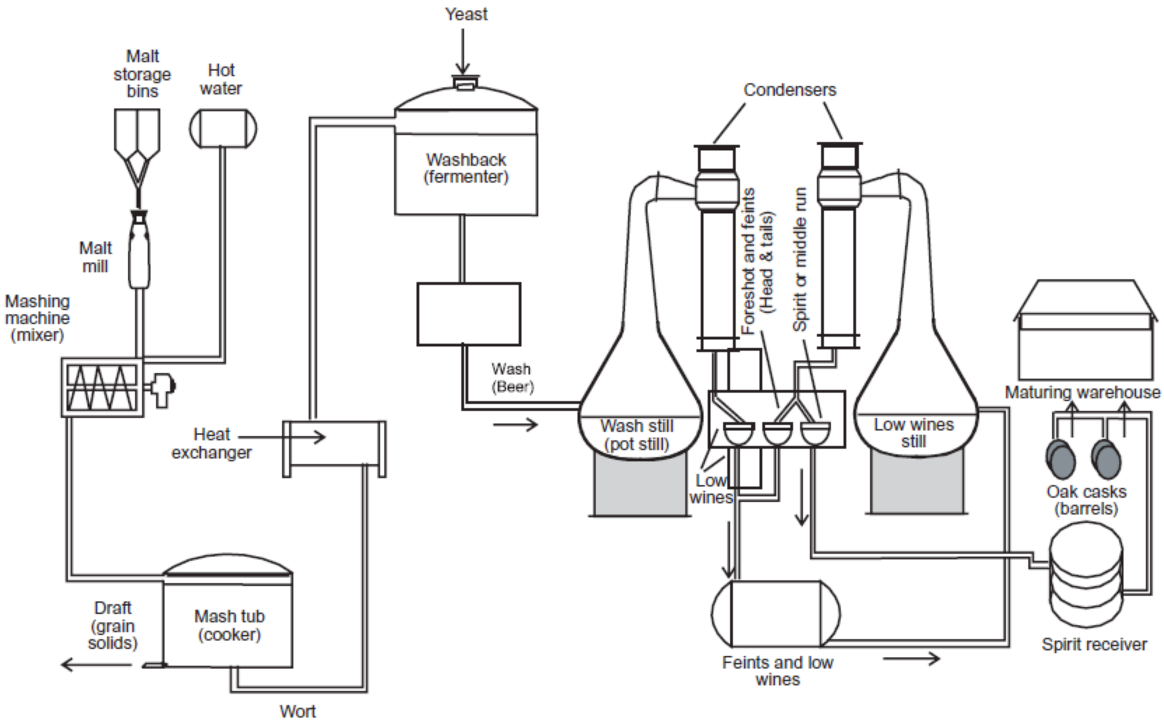

Figure 7 – flow diagram of Scotch malt whisky

Continuous distillation

The process previously described refers to single malt whisky and it sticks to ancient traditional rules that are still in use in some distilleries, since copper has a catalytic effect on decomposing unpalatable traces of sulfuric compounds formed during fermentation, so a copper still ensures a better final taste [11], but there is uncertainty about what other physical and chemical mechanisms affect spirit aroma and thus its quality. For this reason, in some cases, traditional techniques are preferred to modern ones, since the bigger priority is the final quality of a product that is famous for being prestigious and exclusive, also thank to marketing idea that traditional is better and it's worth to be paid more [14]. In ancient times, instead, copper was chosen because it is a good heat conductor, easy to manufacture and durable metal (the mean lifetime of a copper pot still is from 15 to 25 years). Indeed, also the pot still shape influences whisky taste: if it is long and slim, it produces a soft, pure alcohol; if it is short and squat, it gives a strong, intense flavour. Some other distillers, instead, prefer more modern continuous distillation. Column distillation consumes 10% less than pot distillation [21], it doesn't need to be cleaned after each batch and it can be used for unmalted grains, thus resulting in a faster and cheaper production [20]; however, malt whisky must be done in pot still. The column still used nowadays is quite the same as it was in 1830, when Irish excise officer Aeneas Coffey invented and patented an improved, more efficient version of a very complex continuous still created by Robert Stein in 1828, for the production of grain whisky, named neutral spirit (that must be blended with malt whisky). Coffey still was composed of metal trays and wooden walls on the column. It had a great success due to its efficiency, rapidly spreading in Ireland, Scotland and England in the following decades and it was used for a very long time: even now a couple of them are still working (in the original configuration or its variations). Coffey still design is outlined in Figure 8, as it was in 1840 circa [12].

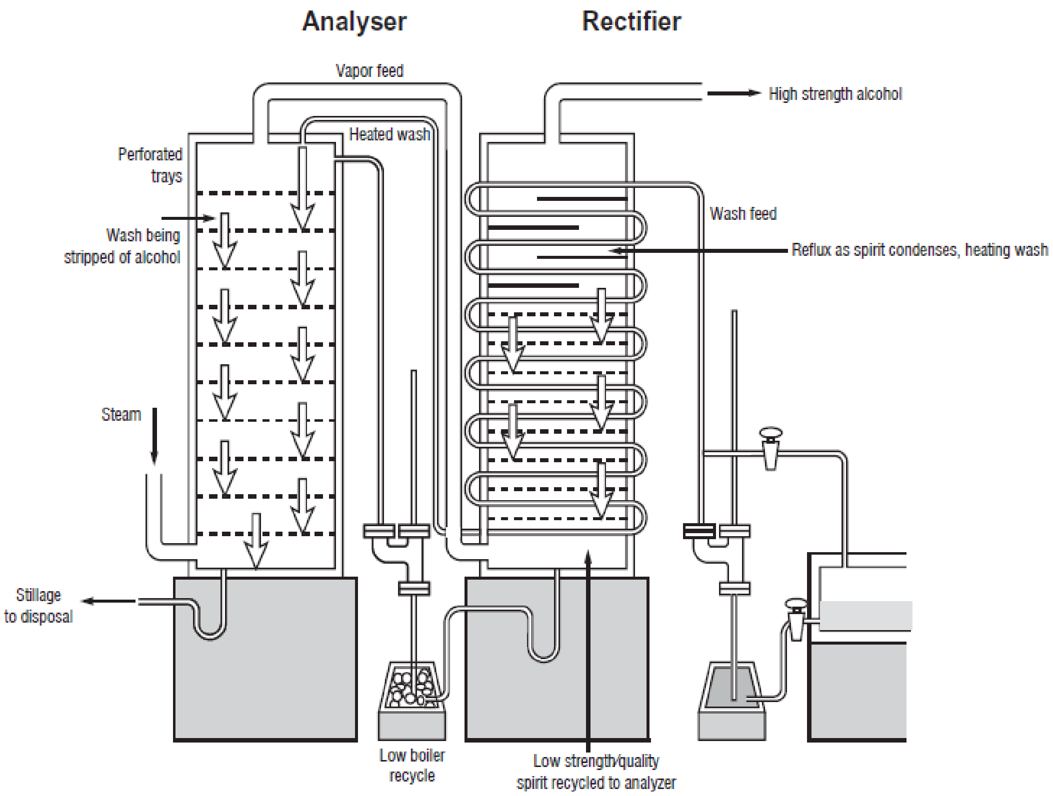

Figure 8 – Coffey still

It is mainly composed by two columns: the beer stripper and the rectifier. Wash undergoes preheating in the rectifier, then enters analyser (or stripper) from above, while steam input is at the bottom of the column, in counterflow. As wash drops down through a series of perforated trays, alcoholic part evaporates, leaves the stripper from the top and goes into the bottom of the rectifier, where it preheats the incoming wash. Low quality spirit is recycled from the bottom of rectifier to the analyser, while stagnating liquid extracted from the analyser is discarded. Alcohol content in rectifier must be higher than 94,17% vol for good quality grain whisky. Steam quantity affects distillation: too much would create foaming, liquid carryover and very little internal reflux, resulting in longer distillation time and thus higher costs, while too little steam gives a bad taste to whisky, that would result "stewed". Modern automation systems were added during years, for example for feeding. [12]

Regions

As already said, Scotch whisky is made only in Scotland, that can be divided into five regions of production: Speyside, Lowland, Highland, Campbeltown and Islay. Figure 4 shows their geographical distribution [22].

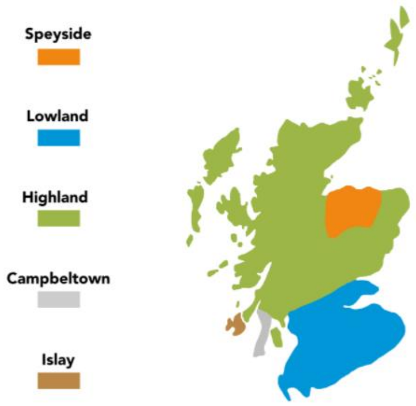

Figure 9 – Scotch whisky regions

Each region has its peculiar characteristics that influence whisky aroma and features: here it is a brief description. Speyside is a fertile region of valleys touched by the river Spey. Here whiskies have notes of fruits, such as apple and pear, honey, vanilla and spices. They are typically matured into Sherry casks. In Lowland soft and smooth malts create lighter whiskies with aroma of grass, honeysuckle, cream, ginger, toffee, toast and cinnamon. Its climate and ground fertility are particularly suitable for barley cultivation, so it is here where most of Scottish barley is grown [20]. Highland is the widest region, it also includes all the islands (except for Islay), it hosts more than 90% of all Scottish distilleries [12]. It comprises a lot of varieties of tastes and characters, different from one another. Campbeltown's whiskies have a strong and full character reminding to salt, smoke, fruit, vanilla and toffee. On the island of Islay (pronounced "eye-luh") there is a thick concentration of distilleries in a land that is almost completely dedicated to the production of a smoky, heavy whisky. [22]

Chapter 2 – Decarbonisation options for a Scotch whisky distillery

A very large quantity of actions can be taken in order to have a more sustainable distillery, but let's first discuss the reasons why a distillery should take the path towards a greener facility.

The first that come to mind are the immediately linked to environment ones, that are: climate change, natural resources depletion, air quality and thus people's health, and so on.

Apart from these, let's say, *noble* reasons, sometimes constraints come into play so that they need to be complied in any case, regardless of one's intention. These can be either rules imposed by national or international institutions, standards required for participating to trade organisations or associations, targets fixed by programs and initiatives, partners expecting a certain level.

Anyway, the sustainability choice can be always convenient, economically speaking. In fact, environmental benefits can be considered a side effect, while cost lowering due to efficiency increase is often the main driver. This happens for two main reasons: firstly, all the variations implying energy savings and some other actions too lead in parallel to money savings and reduction of expenses.

The second aspect is related to marketing and the reputation of a company. The characteristic of being *green,* especially if well promoted, can both attract investors looking for new opportunities and increase by far product sales: several studies confirm that consumers are interested in buying items with green labels, with increasing awareness, and they are even willing to pay an extra price for sustainable drinks (at least this is true for wine, as reported by Schäufele and Hamm [23]).

Methods

Once established the advantages of decarbonising a distillery, let's talk about the methods through which it can be done.

The first pathway can be summed up by the keyword *reduce*. It is very important to bring at the lowest possible value the energy demand, meant in every form of it, avoiding useless waste of energy or uncontrolled losses. This will significatively cut down both direct and indirect emissions, in addition to gain in economic terms. The same considerations hold true for the reduction of usage of natural resources, or any kind of material in general. On the other hand, direct emissions can be reduced, lowering pollutants such as greenhouse gases (first of all CO_2) but also hazardous substances or products that can be dangerous either for people or for the environment.

Strictly related to the concept of reducing, the good practices of reuse or recycle can be applied both in terms of energy and resources. Energy recovery can be put into practice by reusing energy both in the same form and transforming it into another type, and it can be employed again in the same process, in another part of the plant or even in an external facility. Not only energy, but also matter can be recycled, concerning raw materials, fuels, water, by-products, waste, etc…

What can't be reduced or reused, belonging to the essential needs, can be selected mindfully choosing its origins: for example energy could come from renewable sources, materials can be recycled, natural or fully recyclable, crops can be organic and so on.

The Greenhouse Gas Protocol drawn up by World Resources Institute and World Business Council for Sustainable Development can be followed as a general guideline in order to consider all the aspects of emission sources. It individuates three scopes to account for all emissions, direct and indirect, related to a company's activities, that help identifying boundaries to avoid overlapping between two or more different companies. Scope 1 includes all direct greenhouse emissions, that are those coming from sources owned or controlled by the company. As an example they can be emissions related to the combustion for generation of electricity, steam or heat; to the manufacture or processing of materials or chemicals; to transportation with company-owned vehicles; intentional or unintentional releases due to leakages. Biomass and pollutants not included in the Kyoto Protocol are accounted separately. Scope 2 is about electricity purchasing. It is a specific category of indirect emissions, and it is one of the biggest ways to produce emissions. Scope 3, that is optional but still very important, contains all other indirect activities, such as goods and services purchased, external transportation, waste disposal and more. [24]

Options

The list below reports all the possible options for a Scotch whisky distillery to become more sustainable. They were elaborated on a basis of a lot of papers and books from several sources:
[12], [14], [15], [21], [25], [26], [27], [28], [2], [29], [30], [31], [32], [33], [34], [4], [35], [36], [37], [38], [39], [40], [41], [42], [43].

Cultivation

- short-term changes
    - domestic wheat purchasing → cheapest solution
    - imported maize purchasing → greenest solution
- medium- and long-term changes
    - organic grain → expensive
    - *"artificial" non-malt enzymes*

Production

- Production stages
    - Cooking
        - flash steam recovery[1]
        - system type
            - *continuous systems → 40% residence time*
            - batch systems → 20÷40% more efficient, less enzymes adding, easier mechanical agitation
    - Mashing
        - artificial enzymes
        - continuous systems
            - finer grinds of grain → affects spirit quality
    - Malting
        - combined germination and kilning vessels
        - CHP
        - combined steeping and effluent treatment plants
    - Fermentation
        - Carbon Capture[2]
            - Carbon Capture and Storage
            - Carbon Capture and Utilisation
                - purification and sale
            - CO_2 from fermentation (20%) → cold and pure: easy to capture
        - specialized yeasts
        - system type
            - *continuous systems → higher ethanol concentration, shorter fermentation time*
            - batch systems → *cheaper, better aroma, lower ethanol concentration → (better for yeast tolerance)*

  - brewing system
    - Very High Gravity Brewing (for mashes with >18% wt/wt of sugar) → double ethanol concentration, yeast can be recycled, sugar content in mash must be increased
    - High Gravity Brewing (for mashes with 15÷16% wt/wt of sugar) → less solids content in slurry, no viscosity and foaming issues, no need for extra yeast and oxygen, less cooling capacity needed
  - mash pre-heating[3]
- Distillation
  - process type
    - pot still distillation
      - heating system
        - internal steam heating coil → higher efficiency, better control, no base scorching
        - ~~bottom firing~~ → not used anymore
    - *continuous distillation*
      - *material*
        - *stainless steel → cheaper, durable, easy to clean*
        - copper → *very good heat conductor, easy to work with, removes sulphur compounds*
      - *plates design*
        - *fully flooded sieve plates*
        - *bubble caps*
      - *technology improvements/operation*
        - *pressure distillation → columns under pressure*
        - *vacuum distillation → reduced evaporation T (up to 1/3), affects flavour, 91÷92% less energy than pot still*
        - *thermocompressors → Venturi nozzle to boil part of a hot liquid*
        - *multi-effect distillation*
          - *mechanical vapour recompression → heat recovery for next stage reboiler*[4]
        - *extractive distillation column → remove unseparated congeners*
        - *heat recovery*
          - *latent heat recovery of overhead vapours*
          - *exhausted condensate recirculation*
            - *reboilers*[4]
          - *flash steam recovery*
            - *low pressure applications*
              - *wash pre-heating*[5]
              - *cooking*[1]
              - *Cleaning In Place*[6]
          - *heat exchangers*
            - *external applications*[7]
          - *waste heat capture*
            - ©Green Stills
              - latent heat capture
                - powered by:
                  - renewable electricity
                  - hydrogen CHP

            - sent to:
              - thermal storage
              - distillation process
        - *heating system*
          - *indirect: external steam reboilers[4] → less effluent, condensate can be recovered for boiler feed*
          - *direct: steam injection*
  - boiler efficiency maximisation
    - blowdown heat recovery for preheating
    - blowdown only when necessary[8]
      - high quality water for steam
      - conductivity measurement
    - combustion air
      - preheating
      - variable speed fans
    - flue gas
      - continuous monitoring
      - economizer → flue gas preheating boiler feedwater
      - heat recovery
        - internal applications
          - distillation
        - external applications[7]
          - bathing
          - cleaning
          - ...
      - chimney draught fan → minimise fuel consumption
  - heat exchanger type
    - multi-pass shell and tube → way higher resistance to corrosion due to copper
    - plate → higher efficiency
  - pinch analysis
  - wash pre-heating[5]
  - process control and measurement
    - automatic control systems
- Maturation
  - casks reusing
    - scraping and re-charring → wood surface restored
      - casks toasting
        - infra-red heating
        - radio-frequency
        - electroheat technologies
  - spirit evaporation issue
    - prevention → evaporation is essential for spirit aroma → limited
      - maximise cask size (500 L)
      - maximise fill strength (80,4% v)
    - ~~recovery~~ → may alter spirit quality, emission source is diffused → impossible

            - time shortening → legal time specifications → limited
                - control metal-ion catalysts in copper stills
                - ~~other technologies~~
- Plant
    - Maintenance
        - Cleaning In Place
            - with recovered steam6
            - technology
                - sprayballs or sprayjets
                - best spray technology
                    - rotating nozzles
                    - multi-headed robots
                    - high pressure units
            - correct nozzles position
                - vessel shape
                - vessel size
                - particular areas
        - mechanical equipment maintenance
        - cold radiators defrosting
            - use off-peak electricity → lower electricity cost
        - measure water pumps consumption
            - related to water volume and pressure drop → lower electricity cost
        - leaks identification
            - compressed air
                - measure compressor output during stand-by
                - ultrasonic air leak detection
                - air flow meters (on large volumes)

                → lower electricity cost
            - steam
            - other fluids
        - chemicals addition in water → avoid corrosion, but increase blowdown need[8]
            - alkaline pH
            - oxygen scavengers
            - amines
    - Location
        - near upstream supply chain facilities[9]
            - waste heat recovery[10]
        - near external applications for heat recovery[7]
    - Design
        - vessels insulation
        - cover hot liquid surface

        → less heat losses
        - correct sizing
        - no idle equipment
        - high efficiency equipment
        - correct pipe slope (> 1:240) → avoid steam condensation
        - be careful about steam traps

      - design according to start-up (3 times nominal)
      - frequent maintenance
    - do not exceed nominal velocity
    - waste heat recovery[10]
    - LED lighting
  - Resources
    - Water[11]
      - water usage minimisation
        - natural cooling closed loop
      - cooling water reheating
        - turbine
    - fuel
      - fossil fuels
        - Carbon Capture[2]
          - Carbon Capture and Storage
          - Carbon Capture and Utilisation
          - CO_2 from boiler combustion (80%)
      - biomass
        - wood chips → fast to build, cost-effective, proven technology, questionable decarbonisation capacity, needs proximity to woods, limited quantity availability
        - spent grain + wood chips[12]
      - biogas[13]
      - biopropane/bio-oils → scarcity of raw materials, majority consumed by transport sector
      - electricity
        - electrification of heat → requires appropriate grid
          - high T heat pumps (high COP) → expensive, not used in industry yet
        - renewable sources
          - solar energy
            - PhotoVoltaic
            - solar thermal
            - Concentrated Solar Power
          - wind energy
            - onshore
            - offshore
          - sea energy
            - tidal
            - wave
          - geothermal energy → really deep drilling for high T → expensive
          - hydrogen → very expensive

Bottling[14]

- sterilisation and drying
  - waste heat recovery[10]
- location
  - near production plant[9]

Transportation

- supply chain facilities near each other[9]
    - packaging plants close to consumers
- less emitting freight
- bulk shipping
- lighter material[15]
- efficient distribution network

Disposal

- packaging[14]
    - bottle reuse
    - glass recycling → - 40% CO2
        - green glass → higher recycled glass content
    - less material[15]
        - minimize secondary and tertiary packaging
        - lighter glass bottles
            - Narrow Neck Press and Blow technique
        - lighter materials (PET, Tetra Pak...)
    - minimize processing faults → less waste
- wastewater
    - filters
    - anaerobic digestion and membrane filtration
    - treatment with reed beds → prevent copper release
    - waste segregation
    - avoid yeast dispersion → no high oxygen rate
- cooling water[11]
- *odour*
    - *absorption/adsorption*
    - *incineration*
    - *plasma treatment*
    - *perfuming agents*
- solid waste
    - malt dust control
- by-products
    - animal feeding
        - separation
        - evaporation
        - drying
        - wet transport
    - fertilizers
    - fraction of hot pot ale recycling → for cooking and mashing
    - pot ale for mash pre-heating3
    - drying
        - biomass burner[12]
            - CHP
                - anaerobic digestion

        - biogas production[13]
            - onsite use as fuel
                - CHP plant
                - biogas boiler
        - biofuel production
            - bio-butanol → vehicles

Description

A first subdivision was done into life cycle stages, that were considered loosely following the structure of the value chain of a generic industry in beverage sector suggested by Beverage Industry Environmental Roundtable guidance [37]:

- cultivation
- raw material processing
- beverage production and warehousing
- transportation and distribution
- retail, marketing and beverage consumption
- packaging disposal, reuse and recycle

From these, the main stages were identified and further subdivided more and more into detail, analysing different technologies and solutions for each case. Some other practical information, such as a brief description, possible applications, advantages or disadvantages, feasibility or criticalities, effects or incidence, time scale, etc, are sometimes added at the end of a branch (following an arrow (→) in the linear description).

Cultivation

Starting from cultivation of raw materials (that is barley, for Scotch whisky) some choices about where and what kind of cereal to buy can be made: for example national harvest or organic crops.

Production

The stage on which the largest number of changes can be done, and maybe the more effective ones, is production.

Production stages

Cooking can be improved by recovering low pressure steam remained after distillation and by choosing between continuous or batch systems: each of them has its benefits.

Different kind of enzymes and more grinded grain can help mashing, but it may affect whisky's taste. Malting can take advantage of combined heat and power or combine more substages in one.

During fermentation approximately 20% of total carbon dioxide is released, but since it is cold and pure, it can be easily captured and stored or used (for example, once further purified, it can be sold for soft drinks carbonation). Right materials such as specialised yeast can help in this case too. Moreover, the system type selection is important too: continuous and batch systems have their trade-off, while mash preheating, High Gravity Brewing and Very High Gravity Brewing bring benefits to the process.

The choice of process system is crucial for the distillation stage. For traditional pot still distillation, there are no variations that could be done; the only one is related to the still heating system, with an internal coil carrying steam, that is already applied everywhere, since bottom firing with coal is not used anymore. On the other hand, continuous distillation systems offer a wide variety of possible enhancements, starting from equipment materials (copper or stainless steel, each with its qualities), going to column plates design, and ending in an assortment of process techniques. All the measures that can be applied only to continuous distillation system are highlighted with italics characters. Modifying operating pressure in the column at different levels can optimise distillation process in a lot of ways: it can be either pressure, vacuum, or multi-effect distillation; or devices like a thermocompressor or an extractive column can be added. Another effective field in distillation for energy saving is heat recovery. Both sensible and latent thermal energy can be recovered from overhead vapours, exhausted condensate, flash steam or other forms of waste hot streams, in a direct way (recirculation) or by means of heat exchangers, for several applications, in the distillery itself (e.g. wash pre-heating, cooking or cleaning in place) or for external utilities. Waste latent heat can also be captured with industrial patented system Green Stills that, using renewable electricity or hydrogen fed CHP, sends thermal power to a storage or directly back into the distillation process, saving that way up to 70% energy demand. Sticking to continuous distillation, heating system can be switched to indirect type, with outer steam reboilers that allow to save water and energy, instead of direct steam injection. Being boiler the most consuming component (it provides steam for every process, first among all for distillation), increasing its efficiency would strongly impact on overall operation. Efficiency maximisation can be reached with the correct management of flows entering and leaving the boiler, that are water, air and flue gases. Boiler blowdown (feed water substitution) should be done only when necessary, that means that water should be periodically controlled, for example through conductivity measurement, to have a good quality, low impurities presence; when it actually is necessary, heat could be recovered for preheating of new clean water before discharging exhausted one. For an efficient reaction, combustion air can be preheated and its flow can be controlled through variable speed fans (instead of dampers), that are very accurate and flexible. Polluting gaseous emissions should be kept under control by continuous monitoring of flue gas, that can be also seen as a resource, since it still contains thermal energy that can be recovered, for example with an economizer preheating incoming water or with heat exchangers for multiple applications, both internal and external, such as distillation process, cleaning purposes, domestic hot water… Finally, a draught fan applicated to the chimney of boiler, increases its efficiency by minimising fuel consumption. Another trade-off leads to the choice between plate heat exchanger and multi-pass shell and tube type: the first one is more efficient, while the second one resists way better to high corrosion caused by the presence of copper. Pinch analysis is a powerful instrument for the exploration of possible recovery of waste streams; for example, steam leftovers can be employed in wash preheating, as already seen for flash steam recovery in continuous distillation. More in general, for the entire process of distillation, that is the most consuming one, but also for other processes, control and measurement of variables and their properties can reduce losses and increase overall efficiency, for example through automatic control systems that lead the process in the most precise way.

The last production stages are casks filling and maturation. Some kind of whisky production needs brand new oak casks, but they are usually reused for other beverages and then sold to furniture manufactory sector, not to mention that wood often comes from sustainably managed forests. Otherwise, second-hand casks can be used, by scraping and recharring the internal surface of already used casks, restoring them as they were brand-new, and that way reducing wood consumption. As another practice, toasting is a greener alternative to charring, because for toasting modern, more efficient technologies can be used, such as infra-red heating, radio-frequency or electroheating options, instead of burning the internal surface of wood with direct fire. Though, the two operations give different taste notes to the whisky, so it isn’t only a matter of energy saving, but also a product style choice. Since during maturation a significant part of whisky evaporates (the *angels’ share*), solutions to prevent this product loss have been investigated. Casks’ size and spirit fill strength inversely influence evaporation, so they can be maximised to 500 litres casks, filled with 80,4% volume of alcohol over total volume, staying into the conventional boundaries of whisky industry, considering that alcohol evaporation is essential for the formation of the aroma. Another possibility could be the recovery of evaporated spirit from the warehouse ambient, but being the emission source diffused, it is almost impossible and moreover it would affect the delicate product quality, so it is not considered at all. Maturation time shortening would increase a distillery’s productivity, but apart from metal-ion catalysts presence in copper stills and their control (that is not currently used), there is not much that can be done to accelerate storage, considering the legal specifications about aging.

Plant

What can’t be categorized into a single process or production stage, has been labelled under the term *plant*, indicating all those solutions related to the whole distillery design and operation: more precisely location, design, involved sources and maintenance.

Under the big group of maintenance, a lot of aspects are included: one of them is the cleaning in place (abbreviated in CIP) procedure, that is an automated internal machinery washing, without disassembling or removing parts of it. It can be optimised through the technology selection: sprayballs, sprayjets, rotating nozzles, multi-headed robots or high-pressure units or by identifying the correct nozzles position into the component, according to vessel shape and size and areas of particular interest. This can be done with recovered steam from distillation process. Strictly speaking about periodical maintenance, mechanical equipment preservation and cold radiators defrosting improve plant performances. In particular, defrosting can be done in a specific time slot, taking advantage of lower cost of off-peak electricity. Other efforts to reduce electricity costs are water pump consumption measure, that is correlated with pressure drop and water volume, and compressed air, as well as steam or other fluids, leaks removal. Measuring compressor output during stand-by can help identifying leaks in compressed air system; otherwise, ultrasonic air leak detection devices or air flow meters (suitable for large air volumes) can be employed. Addition of chemicals such as alkaline, oxygen scavengers or amines reduces materials corrosion, but on the other hand it increases the need for blowdown in the boiler.

If there is the possibility to choose the distillery location, a site that is near to other facilities in the same supply chain (both upstream and downstream) is preferable; that way transportation is reduced and, in addition, waste heat can be recovered in other installations. Waste heat potential of distilleries in Scotland is estimated to be 320,104 GWh/year, distributed upon 129 different geographical sites, that means an average potential per site of 2,481 GWh, making distillery sector the industry that has the biggest potential, together with wastewater treatment sector. Since typical temperature range for waste heat in whisky distilleries is from 70 to 90°C, it is enough for direct use in district heating (there is no need for upgrading through heat pumps). A proximity analysis revealed that 72% of distilleries are located near an existing heat demand of at least 250 MWh, contributing for 83% of total heat potential, meaning that waste heat can be exploited within 250 m from its generation. The cited analysis didn’t consider possible reuse or recovery of heat internally to the distillery itself, that is another great potential. [44]

In the design phase, it is important to pay attention to some aspects in order to provide the best possible solution. Some advices for correct design include: good vessels insulation and hot liquid surfaces covering (to reduce heat losses), proper sizing, idle equipment avoidance and high efficiency devices preferring, accurate pipe slope calculation (a ratio of more than 1:240 avoids steam condensation), steam traps sizing according to start-up condensate load (usually 3 times higher than nominal one), flows speed keeping under nominal velocity, LED lighting in every involved building (plant, offices, warehouse, visitor centre…) and finally consideration of opportunities to recover any kind of waste heat produced within the plant and subsequent equipment arrangement.

The last feature about a distillery is related to resources consumed to run it. As it is in most industries and in all food and beverage ones, the production of Scotch whisky needs a water source: in fact a lot of historical whisky distilleries rose next to rivers or deep wells. Obviously, the amount of water that ends up into the final product can’t be changed, but a natural cooling closed loop would minimise process water consumption. Alternatively, process warm water could be reheated up to steam and then expanded in a turbine.

Nevertheless, the biggest resources intake is represented by fuels. In case of fossil fuels, the only possibility is carbon capture on boiler emissions, since it is responsible for the production of 80% of CO_2, with successive storage or utilisation. There are a lot of alternatives to fossil fuels, that are, some more than others, sustainable. Among the most questionable ones, there is biomass, such as wood chips, with its well-known pros and cons, like that it is a low cost, fast to build, proven technology but it needs to be near the woods, it requires a large amount of material, that may be not available, and it still emits pollutants, even if it may have net zero emissions. A specific, good characteristic of wood chips is that they can be combined with spent grains, that way reusing a part of the plant waste. Among the family of biofuels, biopropane and bio-oils are not so much used because of the scarcity of raw materials needed to produce them, the major part of which is employed in the transportation sector, as fuel for vehicles. Speaking of biogas, it's a whole different situation: it is currently widely used to fuel large plants like distilleries, that often not only consume biogas purchased from the grid, but also produce it themselves, through biochemical processes involving by-products or waste from the production stage. All the other fuel options can be gathered into the big group of electrical sources. Since the majority of a distillery's energy consumption is thermal, relying only on electricity would mean electrifying heat, that implies the availability of an appropriate electrical grid infrastructure. Moreover, generating high temperature heat (necessary for the production) with electrically fed heat pumps, requires very high COP, that results in high costs. Also substitution of conventional plants with electric ones would imply a serious financial issue related to a long payback time: these are the reasons why electrification of heat in industry is an issue still under study (for further information see [2], [13], [36], [45]). Nevertheless, if electricity can't replace other fuels for thermal energy, it still remains a consistent part of a distillery's consumptions, so decarbonisation can pass through the use of renewable energy sources, both supplied by the grid and self-produced. There are all the possible renewable source alternatives: solar with photovoltaic, thermal or concentrated power; wind either onshore or offshore; sea energy with tidal or wave solutions; geothermal, but with the need of a very deep drilling to reach high temperatures; and green hydrogen, that is nowadays very expensive. Actually, some of the previously mentioned RES allow to directly produce thermal energy, or a combination of thermal and electrical energy. A strong help for RES exploiting is their coupling with storage, either electrical (batteries) or thermal. The potential of steam accumulators or PCM (phase change material) storage devices, charged with distillation steam, in whisky production is investigated by Früh et al [46].

Bottling

At the very end of the production chain, there is the bottling process, that here is handled separately since it often takes place in a different location or sometimes it is even made by a different company. Just speaking about location, the more bottling plant is near distillation plant (or better said near maturation warehouse), the less transportation emissions will be. Before being filled, bottles are sterilised and dried for sanitary reasons: this operation can be carried out with waste heat recovered from main plant.

Transportation

During distribution, a lot of emissions are released due to transportation, but efforts can be done in some aspects in order to reduce them. The most obvious variable is the distance: given that consumers' position is fixed, packaging plants should be located near final destination. In general this is true for every facility dealing with each step in the supply chain: as already told, plants near to each other means less ground to cover. For equal distances, less emitting freight mode are preferable, meaning the vehicles with better characteristics (for example trains instead of trucks or ships instead of airplanes). Always speaking of constant journey, transporting more material at once, for example in bigger containers or bulk shipping, is more efficient. Containers' weight directly influences carbon footprint too. Concluding, an efficient distribution network has a good impact on transportation.

Disposal

The last step in a product's life cycle is the disposal of every waste material generated until then.

Packaging

Thinking about product final consumption, packaging is an issue to consider. Bottles reusing, for example with a system of returnable containers, would be an optimal measure, but also glass recycling is a valid opportunity, reducing CO_2 emissions by 40%. In particular, green coloured glass is more sustainable than clearer one because it can be produced with a bigger recycled cullet share. Packaging material can be reduced by minimising secondary and tertiary packaging or by lightening primary one. If lighter materials for packaging like Tetra Pak or PET can affect product conservation and, above all, they have a negative impact on customers' quality perception, 10% lighter glass bottles, made of a thinner layer of glass (for example with Narrow Neck Press and Blow technique), are almost unidentifiable from traditional thicker bottles and do not affect customers' satisfaction, while lowering CO_2 emissions by 10%. Moreover, minimising processing faults during bottles production results in less material to be discarded.

Water

From whisky distillation remains a wastewater, containing water, oily fats, alcohol and other traces, and that stream can't be simply discharged into a river as it is. Its treatment can take place through filters (such as a mesh grid to retain grains), anaerobic digestion with membrane filtration, reed beds to eliminate copper traces, waste segregation or by reducing the dispersion of yeast during fermentation, that would higher the oxygen demand for treatment. The other outgoing water flow is exhausted cooling water, whose greener alternatives have already been analysed in the resources section.

Odour and solid waste

Continuous systems generate odour releasing problems, that can be solved with techniques of absorption or adsorption, incineration, plasma treatment or perfuming agents adding. The only strictly speaking solid waste produced is malt dust, whose release has to be kept under control.

By-products

The other solid or mixed solid-liquid leftover materials can be considered by-products rather than waste, since they can be utilised in useful and cost-effective applications. The following whisky by-products can be recovered for energetic purposes:

- Draff: it "is the spent grain left in the mash-tun after the wort has been drawn off."[47] It constitutes the solid part of residues. More or less 2.5 – 3 kg of draff are created for every litre of whiskey. [17]
- Pot ale: it is "the liquor left in the wash still after the first distillation in the pot still process. It is the residue of the wash after the extraction by distillation of the low wines."[47] It "resembles a pale yellow, golden liquid, with a malty, burnt cereal and yeast aroma."[48] It contains yeast (the insoluble soldi fraction), barley, soluble protein and carbohydrate, traces of copper [49]. Every litre of produced whiskey, from 8 to 15 litres of pot ale drain. [17]

The oldest disposal practice is represented by landfilling, possibly after biodrying process, but it's also the more polluting one. Other greener paths can be agricultural ones, such as composting or animal feeding, after different treatment techniques such as separation, evaporation and drying, or simply transported as it is, that is to say wet. Typically, by-products treatment processes (for re-use or sell) consume about 30% of total distillery demand [43]. Pot ale syrup, that is made by concentrating it though evaporation, can be sold for animal feeding at about 60£ per tonne [49]. Another agricultural use, that was very diffuse in the past and still in use today, was to use by-products as fertilisers, so that they can be sold to neighbouring farms. Pot ale can be internally recycled in the distillery as a fraction of cooking and mashing material or for preheating incoming mash with its warm temperature. After being dried, spent grains can be combusted in a biomass burner, together with other biomass fuels, feeding a Combined Heat and Power system for the alimentation of distillery itself or for other plants.

A good alternative to recover by-products' energy content is given by anaerobic digestion, with subsequent production of either biofuel or biogas. Anaerobic digestion is particularly convenient for alcoholic beverages sector, where the production of alcohol helps breaking down organic matter, so it facilitates digestion process. A study demonstrated that the best technology to turn draff into fuel is anaerobic digestion, for the production of biogas. The same process is valid for pot ale and spent lees, too [50]. Research about anaerobic digestion use for distilleries waste has been since the 1970s [13]. While production of biofuels such as bio-butanol is mainly addressed to vehicles, biogas production provides several advantages in industry, especially if employed in the same factory where waste is produced, or at least in the same site; as a fuel, biogas can either be burnt in a traditional boiler or in a CHP plant. One of the advantages is that, of course, there is no need for waste disposal, thus avoiding all logistics and expenses related to it and at the same time reducing environmental impact: final waste after anaerobic digestion treatment, called digestate, is not only less bulky and by far less contaminant, but it also can be used as a fertilizer. This implies that digestate could even be sold (for up to 17 £ per tonne) representing, although humble, an income source, but more frequently it is picked up for free by final users, so it would be a good idea to exploit (also economically) leftovers before getting rid of them. Also, stillage resulting after anaerobic digestion process is much drier, so it can be stored more easily and for longer times into "cakes", before being used as animal feed. Formerly it was processed into huge driers, but this old system was extremely more energy intensive and thus expensive. The other important advantage of employing biogas to run a beverage facility is that, since digestion is fed with plant's own exceeding material, there is no need to purchase natural gas or any other fuel in order to produce heat necessary to beverage production process (or in the worst case, this external buying is by far reduced). In addition to that, the plant is operated with biogas, that is a renewable energy source and so the entire system creates overall less emissions also by using green energy. The issues related to an anaerobic digestion plant are that it requires a lot of space and periodic maintenance, it consumes electricity, it does not have a high reliability, and digested sludge needs to be treated and disposed properly [14].

Comments

At this point a question arises: among all these opportunities, which one is better to choose? Unfortunately, there is no absolute answer. Not all the options are applicable to every distillery: it depends on its size, location, existing equipment, sources availability, financial capability etc…, so as a first step, one should consider only the improvements that are suitable for a precise factory. Then, a good recommendation is not to focus on a single measure, but to take into account a combination of several different optimisation settings that together can upgrade the distillery to a more sustainable condition. Sometimes merging more than one decarbonisation alternatives is a real necessity, as it is for example in Scotland, where there is not a renewable source that is present in enough quantity to satisfy the entire distillation industrial sector [41]. In addition, a whole lot of variations are related to other ones, thus creating the possibility of multiple combinations of configurations. Some of these correlations are marked in the linear list with numbered notes that remind of each other, linking two or more solutions.

Speaking about the importance to apply a series of different actions, some of the previously analysed ones were taken by distilleries such as Nc'nean one, that has been the first distillery in UK to reach carbon neutrality. This example demonstrates the feasibility of a change towards greener plants for every facility in the spirits sector. At Nc'nean, they use only renewable energy for both electricity and heat demand: their biomass boiler is fed with woodchip coming from a near forest (replaced by new trees) and they purchase certified 100% renewable electricity. They use as raw material only national organic barley, send exhaust draff as feedstock for cows and fill 100% recycled glass bottles with their product (just by doing that, carbon footprint is reduced by 40%). Plant design allows to save 80% of water, thanks to a natural cooling closed loop. All these measures together allow to have the lowest possible carbon footprint; although, since it is still not null (about 2 kg of CO_2 equivalent per litre of whisky produced), they rely on carbon offsetting for having a net zero emissions whisky. [33] [51]

Chapter 3 – Anaerobic Digestion

One decarbonisation option that is already in use in some distilleries is anaerobic digestion of by-products. Let's go deeply into details to explore anaerobic digestion's potential.

Anaerobic digestion is a natural process occurring when some organic matter decays, releasing gas into the environment. It can though be controlled to take advantage of the gas produced by collecting it. To do so, organic feedstock is inserted into an airtight container, where bacteria, under the right environmental conditions, digest it, releasing biogas. The general chemical reaction can be represented by the transformation of glucose molecule into methane and carbon dioxide:

$$C_6H_{12}O_6 \rightarrow 3CO_2 + 3CH_4$$

Anaerobic digestion follows four subsequent stages:

- Hydrolysis: big, complex polymers are broken into smaller monomers.
- Acidogenesis: monomers are further decomposed, forming volatile fatty acids, ammonia, carbon dioxide and hydrogen sulphide.
- Acetogenesis: acetogens create acetic acid from all former substances.
- Methanogenesis: finally, biomethane is produced (together with water). It usually contains 60% of methane and 40%

There are different kind of processes gathered under the name of anaerobic digestion, depending on a series of parameters, that can be used to make a classification. Moisture content in initial feedstock separates wet systems, working with a range of 5 – 15% of dry matter, from dry systems, digesting a feedstock with more than 15% in dry matter. According to the operation temperature, process can be either mesophilic, from ambient temperature of 25°C to 45°C, or thermophilic, around 50 – 60°C. At last, there is a difference in the process itself that affects also containers' configuration. If the feedstock is put into digester altogether, it is called batch, while if there is a constant input of matter in time, it's a continuous flow process, that can take place in a continuous-flow stirred tank (CSTR) or in an upflow anaerobic sludge blanket (UASB), that is more indicated for very liquid waste, faster but also a little more sophisticated and thus more difficult to keep under control compared to CSTR. [52]

Certain conditions can assure a higher biogas yield if controlled properly. For example, digester sealing, by keeping the container airtight, prevents biogas produced to leak out and air to break in and dilute it with oxygen. Retention time in the digester varies from feedstock to feedstock, but each waste has its own optimal time of staying to produce the more biogas. Also increasing the total number of tanks can help digestion process, if in each container there are different conditions, suitable for each specific digestion stage. There are, instead, optimal conditions that are common to every matter, such as pH, that has to be in the range of 6.8 – 8.0 for the microorganism to work. A similar case is represented by moisture level: if it is too low, the feedstock cannot mix with microorganisms but if it is too high, there is not enough organic matter for the process to occur. Another important parameter to keep an eye on is the C/N ratio, namely the relation between carbon and nitrogen content in the feedstock material: since bacteria consume carbohydrates and proteins in a proportion of 30:1, the maximum biogas yield would be obtained if there was 30 times carbohydrate than protein, but a C/N ratio of 15 – 30 can be considered acceptable. [43]

By-products potential

Soft drinks

Research about treating soft drink production wastewater has been done for years because it is easily biodegradable thanks to its components, mainly: fructose, glucose, sucrose, lactose, artificial sweetener, fruit juice concentrates, flavouring agents, dissolved carbon dioxide/carbonic acid, bicarbonates, colouring agents, preservatives (phosphoric acid and tartaric acid) and mineral salts. [53] Most of papers in previous literature analyses wastewater treatment with the aim of reducing its pollutants and reusing purified water after some kind of filtration. However, all of these processes involve (at least as one of the stages) anaerobic digestion reaction, that releases a certain quantity of biogas, so a biogas yield can be measured or calculated after experiments.

Kalyuzhnyi et al. [54] compared two different laboratory reactor types: a 1.8 litres Up-flow Anaerobic Sludge Blanket (UASB) and a 3 litres hybrid reactor-sludge bed. Both of them were kept at 35°C and feed with wastewater coming from a continuous soft drink processing factory in Mexico and then added with 0.5-1 g/L NH_4Cl and 1-6 g/L sodium bicarbonate. Wastewater properties ranges are in Table 3.

COD_{total} [g/l]	**$COD_{soluble}$ [g/l]**	**TS [g/l]**	**VS [g/l]**	**pH**
1.1-30.7	1.0-27.4	0.8-23.1	0.6-15.7	4.3-13.0

Table 3 – wastewater properties ranges

The biogas resulting from anaerobic treatment was composed by 60-65% of methane, whose yield was measured to be 320-330 $Nm^3/t_{\text{COD consumed}}$.

Another analysis [55] about soft drink wastewater treatment was carried with a sample of wastewater collected from a bottling company in Nigeria, processed in a 10 litres anaerobic batch digester at ambient temperature (27°C). Proximate analysis data are summarized in Table 4.

pH	**TS [%]**	**VS [%]**	**Moisture [%]**	**C/N ratio [%]**
9.52	5.0	2.5	95	5.95

Table 4 – proximate analysis data

After the treatment of 9 litres of wastewater, a total biogas production of 80 ml was measured, so an approximated biogas yield of 0.0089 $m^3_{biogas}/ m^3_{wastewater}$ can be assumed. The author stated that the process can be optimized with the presence of inoculum and with a larger digester.

A four-stage treatment of soft drink wastewater was carried on in [53], on sample collected from a carbonated soft drink and carbonated flavoured water industry in South Africa. The plant was made of a laboratory-scale expanded granular sludge bed reactor (EGSB) and a successive aerobic membrane separation unit (MBR). Anaerobic digestion took place at a temperature of 35-37°C, in the digester tank with a capacity of 24 litres, inoculated with 9 litres of granular anaerobic inoculum taken from a full-scale UASB reactor treating brewery wastewater, in South Africa.

Organic loading rate and corresponding biogas flowrate of different operating stages are collected in Table 6, while average percentage concentrations of components in the produced biogas are in Table 5.

CH_4 [%]	**CO_2 [%]**	**H_2S [%]**	**N_2 [%]**	**O_2 [%]**
70	11	0.6	14.8	4.1

Table 5 – percentage concentrations in biogas

From the definition of Organic Loading Rate, the biogas yield for each stage can be calculated: $Yield_{biogas} = \frac{flowrate_{biogas}}{OLR \cdot V_{digester}}$. Results are as well included in Table 6. An average value among all yields of 72.29 m^3/t_{COD} comes out.

Operating stages	**OLR [kg_{COD}/m^3 d]**	**Average biogas flowrate [l/d]**	**Biogas yield [m^3/t_{COD}]**
Start-up 1	0.9	2.5	111.6
Stress test	5	8.8	73.33
Start-up 2	5.1	9.5	77.61
Mode – 1a	5.1	8.6	70.26
Mode – 1b	2.7	6.2	95.68
Mode – 2a	7.6	7.9	43.31
Mode – 2b	6.2	2.7	18.15
Mode – 3a	10.9	16.7	63.84
Mode – 3b	9.9	23	96.80

Table 6 – organic loading rate, biogas flowrate and yield

A specific study [56] about biogas yield of soft drinks was made in India, where carbonated soft drink sludge (CS) coming from a bottling company was mixed with other organic waste in different ratios to enhance biogas yield. Those waste were: palm oil sludge (POS), soybean cake waste (SW), rice husk (RH) and pig dung (PD). Anaerobic digestion took place at 24-32°C ambient temperature, in 1 m^3 bio-digesters filled for three quarters with mixtures and water (that was added depending on original moisture content). All relevant data are collected in Table 7.

	CS	**CS+POS**	**CS+PD**	**CS+RH**	**CS+SW**
CS [%]	100	55	70	29	33
Moisture [%]	71.4	91.82	63.00	11.00	47.1
Water added [kg_{water}/kg_{sludge}]	2	2	2	3	3
Total wet feed [kg]	45	42.91	72	48.95	36.68
pH	5.7	4.45	6.60	7.15	7.5
Cumulative gas production [l]	86.50	43.62	171.75	100	121.50
Biogas yield [m^3/t]	1.92	1.02	2.39	2.04	3.31

Table 7 – relevant data of soft drink sludge

Biogas yield is calculated dividing gas production by the total mass of slurry input. Extracted gas percentage composition of some cases are reported in Table 8.

[%]	**CS+POS**	**CS+RH**	**CS+SW**
CH_4	75.5	71.5	70.8
CO_2	21.0	19.8	21.7
CO	2.3	8.0	7.2
H_2S	1.2	0.7	0.3

Table 8 – gas composition

Brandy

Some research among previous literature for energetic using of grape marc has been done.
R. Moletta [57] makes a reference as an example of anaerobic digestion of vinasses in a plant in the Cognac region (France). REVICO company has 4 digesters (with a total volume of 17 500 m^3) kept at 37°C, where overall about 70-80 tons of vinasses are processed every day, with a flow of 100 m^3/h. [58] Its biogas production is 0.65 $m^3/kg_{COD\ removed}$, with a fraction of 65% methane [57].

Colussi et al. [59] developed a model that simulates an anaerobic continuous flow stirred tank (CSTR) treating winery waste in the form of substrate composed by a mixture of exhausted grape marc and wine lees, with a ratio of 5.16 grape marc/wine lees. Exhausted grape marc is less biodegradable than fresh one. Simulator has been used to investigate the possibility of self -sustainability of a distillery in northern Italy. Table 9 and Table 10 indicate respectively simulation input parameters about input flow of substrate and calculated biogas flowrates of both whole substrate and only exhausted grape marc.

Feed flowrate [l/h]	10
Total Solid$_{Feed}$ [%]	33

Table 9 – simulation input parameters

	Q_{CH4} [Nl/h]	**Q_{CO2} [Nl/h]**
Exhausted grape marc + wine lees	956	728.7
Exhausted grape marc	812	766.8

Table 10 – calculated biogas flowrates

From previous data, methane and biogas yield can be calculated as $Y_{CH_4} = \frac{Q_F}{Q_{CH_4}}$; $Y_{biogas} = \frac{Q_F}{Q_{CH_4} + Q_{CO_2}}$.
Results are in Table 11:

	Y_{CH4} [Nm^3/l]	**Y_{biogas} [Nm^3/l]**
Exhausted grape marc + wine lees	1.05e-5	5.94e-6
Exhausted grape marc	1.23e-5	6.34e-6

Table 11 – calculated methane and biogas yield

Other several studies about utilization of grape marc refer to the one coming from industrial wineries, while there is less information about distilleries waste products made of grape. However, in [15] the distinction between wineries and distilleries production is very clear and definite. It distinguishes between fresh grape marc, from wine production, and exhausted grape marc, from distillates production. Each of them is further divided according to the colour of grape used (red or white).
Primary and proximate analysis of all by-products are reported in Table 12:

Marc type	**Grape colour**	**% volatile solids (on dry basis)**	**% moisture**	**HHV (on dry basis) [kJ/kg]**
Exhausted	*White*	98	60	21.707
	Red	98	54	18.494
Fresh	*White*	98	65	20.494
	Red	98	59	20.274

Table 12 – primary and proximate analysis

In general, there are major differences between characteristics of red and white grape than there are between fresh and exhausted grape marc.
An elemental analysis on grape marc was performed in [15], too. Results are reported in Table 13:

Marc type	**Grape colour**	**N [%]**	**C [%]**	**H [%]**	**O [%]**	**Cl [mg/kg]**	**Hg [mg/kg]**
Exhausted	*White*	1.71	49.99	6.48	39.82	<50	0.001
	Red	2.36	43.83	6.41	45.40	<50	0.002
Fresh	*White*	2.34	48.43	6.74	40.49	<50	0.014
	Red	2.29	50.23	6.24	39.24	<50	<0.05

Table 13 – elemental analysis

In this case differences between marc types are more visible, even if they have still quite similar composition.

The main purpose of [15] was to look for a method to calculate Anaerobic Biogas Potential, rather than obtaining it experimentally through laboratory tests, which leads to reliable results, but it can take long times (up to 100 days). The new approach consists of measuring in laboratory (in standard conditions), with either static or dynamic tests, the respirometric index (RI) of samples. RI is defined as the "quantity of oxygen consumed by microorganisms per unit of present volatile solids and over time" [15]. After that, the anaerobic biogas potential (ABP) can be estimated through some correlations.
The results of that study were found to be acceptable, since they are comparable to other sources in literature. That is why for this case Anaerobic Biogas Potential [Nm^3/t] data in Table 14are assumed [15].

Marc type	**Grape colour**	**ABP max$_{VS}$**	**ABP min$_{VS}$**	**ABP max$_{tq}$**	**ABP min$_{tq}$**
Exhausted	*White*	86.35	78.64	33.64	30.64
	Red	80.56	73.16	35.90	32.60
Fresh	*White*	120.72	111.17	41.02	37.77
	Red	125.81	115.998	51.36	47.35

Table 14 – Anaerobic Biogas Potential

VS is the biogas yield based on volatile solids, while *tq* involves the total matter. Concerning distilleries, exhausted white grape marc value is of particular interest. As it can be noted in Table 14, biogas yields turn out to be much smaller than ABP resulting from fresh white grape marc.
Anyway, a brief review of biogas potential production from wine waste is reported below, as a mean benchmark.

Table 15 indicates measures on two grape species of a batch mesophilic anaerobic digestion process in a micro-scale reactor. [42]

	Moisture [%]	**Total solids [%]**	**Volatile solids [%TS]**	**Ashes [%TS]**	**Specific biogas yield [Nm^3/t$_{VS}$]**	**Methane content [%]**	**Biogas potential [Nm^3/t$_{tq}$]**
Nero buono grape marcs (red)	49.89	50.11	94.23	5.77	322.01	48.71	152.02
Greco grape marcs (white)	72.11	27.89	93.14	6.86	405.66	67.32	105.38

Table 15 – measures on two grape species

Table 16 reports chemical and physical characteristics of grape marc with no specified provenience, in addition to methane and biogas yields. It was all measured in batch trials according to Standard Procedure VDI 4630 (2006). [60]

pH	Total solids [%]	Volatile solids [% TS]	Biogas yield [m^3/t_{VS}]	Methane yield [m^3/t_{VS}]	Biogas yield [m^3/t_{tq}]	Methane yield [m^3/t_{tq}]
3.58	61.4	90.7	250	116	139	65

Table 16 – characteristics of grape marc

El Achkar et al. included in their study the difference of performances between whole grape pomace and grape pomace after a grinding mechanical pre-treatment, but hereafter only untreated grape marc is considered. Measures upon batch anaerobic digestion were made in a laboratory pilot plant. The variety of grape was Cabernet Franc, whose characteristics are showed in Table 17, together with methane yield and theoretical potential. [61]

pH	Total dry solids [%]	Volatile solids [%]	Chemical Oxygen Demand [%]	N [%]	P [%]	Water [%]	Methane yield [Nm^3/kg]	Theoretical methane potential [Nm^3/kg_{COD}]
3.94	43.4 ± 0.5	37.1 ± 0.5	61.0 ± 0.3	0.70 ± 0.02	0.22	56.6	0.205	0.134

Table 17 – measures on Cabernet Franc

Scotch whisky

In literature, several analyses were carried on to investigate the energy potential of converting whisky distilleries waste through the process of anaerobic digestion. A practical example is made in [52], where a case study is performed on 8 different Scotch whisky factories located in the isle of Islay, Scotland (UK), with a total annual production that is over 16 million litres. Data about draff and pot ale derive from a report about real facilities: they are provided by Schmack company, that deals with design, construction and maintenance of biogas and biomethane plants. Table 18 sums up main features of by-products and the possible biogas extraction. These values are considered valid for the production of a poor biogas, composed for 55% by methane and the rest 45% by carbon dioxide.

	Dry matter [% TS]	Biogas yield [m^3/t_{TS}]
Draff	21.7	628
Pot ale	4.38	700

Table 18 – by-products features

Another research involving real plants is made in the project by Meadows [43]: 9 different Scotch Whisky industries in the United Kingdom provided actual data. Their size is diversified, with productions that vary from 20 000 to 10 000 000 litres of whisky per year. In Table 19 there are daily draff and biogas production, as reported in [43]. In Table 20 same data for pot ale are present, but on annual basis, as [43] lists, and only for distilleries that provided them.

Distillery	kg_{draff}/day	l_{biogas}/day
A	10274	4354207
B	15	7200
C	8668	3673790
D	6121	2593947
E	39726	16836269
F	986	418004
G	16893	7156478
H	22685	9614090
I	68493	29028050

Table 19 – daily draff and biogas production

Distillery	$m^3_{pot\ ale}$/year	m^3_{biogas}/year
A	2200	55000
C	38250	573750
E	101376	1520640
F	2200	33000
G	38250	573750
I	150826	2262390

Table 20 – yearly pot ale and biogas production

In order to obtain biogas yield, simple calculations are made. Average values are:

Draff biogas yield= 0.4238 m^3/kg Pot ale biogas yield= 15 m^3/ m^3

A large distillery in the Republic of Ireland is analysed in [13] and since the plant produces not only whiskey, but also other spirits, its waste is made of draff, thin stillage and thick stillage. Thin stillage is the liquid remaining after the distillation of pot ale, while thick stillage is the solid-liquid mixture remaining after the distillation of maize in a continuous distillation column. In Table 21 their properties on wet weight basis, together with methane production (a digestion efficiency of 80% is considered) can be found. Experimental assays in triplicate using glass fermenters in controlled laboratory conditions were performed to find these data.

	Total solids [$\%_{wwt}$]	Volatile solids [$\%_{wwt}$]	Biochemical Methane Potential [m^3_{CH4}/t_{VS}]	Methane yield [m^3_{CH4}/t_{wwt}]
Draff	27.6	26.5	330 ± 2.2	87.4 ± 0.58
Thin stillage	3.9	3.5	494.6 ± 41	17.4 ± 1.44
Thick stillage	8.8	8.2	502.6 ± 42.7	41.4 ± 3.52

Table 21 – properties on weight basis and methane production

Since pot ale and draff have different chemical characteristics from one another and they need different treatments: for example, draff takes a longer time in the digester, while pot ale usually needs to be diluted with spent lees or water, because it has a too high Chemical Oxygen Demand. For these reasons, a higher biogas yield can be obtained if the two by-products are processed separately.

Nevertheless there are studies where they are considered together in the anaerobic digestion model: in [62] the same methane yield of 385 m^3/t_{VS} (volatile solids=91%) is assumed for both draff only and a mixture of draff + pot ale. On the other side, in [63] there is a comparison between pot ale only and variable quantity mixtures of pot ale and draff (50%, 75% and 83%). Biogas generation approximate values are collected in Table 22.

	Volatile solids [g/g_{sample}]	Biogas yield [m^3/t_{VS}]
Pot ale	0.077	205
50% pot ale, 50% draff	0.161	120
75% pot ale, 25% draff	0.134	160
83% pot ale, 17% draff	0.114	240

Table 22 – biogas generation

Biogas yield overview

Table 23 extracts a value of biogas yield for each by-product/waste handled so far, together with main information about digester and methane content into biogas, in order to have a clear view and easily compare data to each other.

Feedstock	**Digester**	**Biogas yield**	**Methane content**	**Reference**
Soft drink wastewater	1 m^3 laboratory batch digester	1.92 m^3/t	75%	[56]
Vinasses	4 industrial units (17 500 m^3 tot)	650 m^3/t	65%	[57]
Pot ale	Industrial UASB	700 m^3/t	55%	[52]
Draff	Industrial CSTR	628 m^3/t	55%	[52]

Table 23 – biogas yield overview

Chapter 4 – Models

In order to explore a facility's potential, design it and dimension its components, system models are a very powerful tool that can be utilised in several different ways. Let's discuss about models and explore this subject.

System models

Usually a study focuses on a single subject that is the objective of the study itself, but things can be different if you want to analyse a more complex and comprehensive situation: there may be the necessity for a system analysis, that takes into account also interactions between the main object and its surrounding environment. The first one in history to introduce system approach to studies was biologist von Bertalanffy in 1956, and his concept turned out to be more and more relevant throughout the years in many other areas.
For what concerns the energetic world, for example, power production is energetically huge, but it isn't the only energy consuming sector, so that interconnection between different fields assumes an important role.

Or even the interdependency between electricity, heat and transports is crucial, thus models that give an overall framework point of view are fundamental.
Sector coupling can reach another level when dealing with storages or interrelated grids, that bring out significant advantages and that are essential for renewable energy sources integration, but on the other side they make systems more and more complicated under political, economic, financial, as well as technological point of view. [64] In these cases, system analysis is the only way to study the entire energetic system, by the means of an energy system model. Previous considerations apply to any scale, from little areas to a model that represents the entire world.

Several users can take advantage of energy system models as a mean of simulation of reality. They can be electricity companies for their expansion plans or decision support about load dispatch and network management; or they can be national administrators for decision making on questions that involve economic growth, energy demand increase, infrastructure maintenance or emissions limitations; of course also researchers can widely profit from energy simulators. [65]

Bottom-up and top-down models

Besides that, two opposite approaches exist when creating a model, corresponding to two respective model classes. Top-down models, also known as macroeconomic, mainly aim to insert the energy system into the general national economy, which is strongly related to, and they are specifically suitable for long term scenarios.[65]
On the other side, bottom-up approach leads to techno-economic models, that neglect linkages with external economy (simplifying them with assumptions)[66], but focus instead on technical details and the different effects of policies, efficiency and cost on the energy system.[64] In particular, bottom-up models' purpose is to optimize energy system operation, through improvement of its efficiency.[65]

Open-source models

In general, the concept of open source can be applied to a variety of different fields, since its meaning is that a software, a tool or a publication is provided for free to anyone who wants it.[67]
In particular, here we are dealing with energy system models and thus being totally open source would mean that not only the software is accessible, but also its own source code and hopefully the involved data set.[68]

There are a few reasons why developers let their work to be publicly available: the most important may be to spread information, and thus increase trust in results, among a wide range of users, including people that have a very basic knowledge about energy systems or who has no experience in the field, such as non-technical decision makers. [69]
Another main purpose is promoting collaboration between different entities or single users that can take a ready model as reference and then improve it, for example by expanding its application or by adding new functionalities or by enhancing the level of detail or by increasing the accuracy or simply by verifying results reliability. [70] This, helped by a structure that is often modular, will ensure a progressive development and further improvement that will let the model get better and better [69]. The very same modularity brings an appreciable advantage, that is open source tools are usually easy to understand and there is no need of too much time to learn how to use them [71]. The last and more trivial issue is that they don't have to be purchased, thus being particularly suitable for students, amateur users, developing country researchers and in general who cannot access to big amounts of money. [72]

While historically energy system models have been under commercial licenses, recently the interest in open source tools has increased, allowing institutions and organizations to develop more and more open software for energy management. [67] Also United Nations, according to 2030 Agenda's Sustainable Development Goals, promote the creation and utilization of open modelling tools for energy planning and policy analysis. [71]

It is important that the source code is completely transparent and editable, so that critical reviewers coming from various areas can fix potential errors and add new aspects from technical, environmental, economic and social point of view. For example, since a model needs simplifying assumptions to be run with an acceptable computational time, a user could be able to check if these assumptions are coherent with reality or, instead, they are unconsciously shaping the model in order to lead to desirable results. Also the comparison between different tools will be easier if all their features can be seen and evaluated, for example in order to highlight strength and weakness of each one. [69] Another concern is that with a non-completely transparent source code the effect of highly sensitive parameters may be hidden. [73]

Models review

In Table 24 some of the most diffused energy system models are considered and briefly analysed. Similar kind of tables (or more in general comparisons between different energy models) can be found in several papers: [65]–[68], [73]–[76] .

NAME	FULL NAME	DESCRIPTION	APPLICATIONS	DEVELOPER ORGANIZATION	YEAR	OPEN SOURCE	CODE AVAILABILITY	PROGRAMMING LANGUAGE	INTERFACE	DEMAND INCLUDED	INDUSTRY
ATLANTIS [77]	/	techno-economic model of the European electricity sector	electricity prices, infrastructure development, integration and costs of renewable energies, simulation of energy shortages, power demand side management (PDSM), regulatory approaches and market directives	Institute of Electricity, Economics and Energy Innovation, Graz University of Technology	2002	no					
Balmorel [78]–[81]	Energy system model	model for analysing the electricity and combined heat and power sectors in an international perspective	security of electricity supply, flexible electricity demand, hydrogen technologies, wind power development, the role of natural gas, development of international electricity markets, market power, heat transmission and pricing, expansion of electricity transmission, international markets for green certificates and emission trading, electric vehicles, environmental policy evaluation	Elkraft System; Risø National Laboratory; AKF Institute of Governmental Research; Stockholm Environment Institute; Institute of Physical Energetics; Lithuanian Energy Institute; PSE Poland; Kaliningrad State University	2001	yes, but purchase GAMS	yes	GAMS	no	electricity, heat	different types of demands can be defined
Calliope [82]–[84]	A multi-scale energy systems modelling framework	framework to develop energy system models, with a focus on flexibility, high spatial and temporal resolution	planning energy systems at scales ranging from urban districts to entire continents	ETH Zürich; University of Cambridge	2013	yes	yes	Python	both line-command interface and API (application programming interface) available	can create any custom demand	conversion technologies and energy carriers
CEEM [85]	Community-scale Energy and Emissions Modelling	tool that allows local governments to assess the impact of projected land use changes on future energy use and GHG emissions through different transportation patterns and the built environment	explore the GHG and energy implications of future land use development	British Columbia Climate Action Toolkit	2007	no					
CIMS [86]	/	integrated energy–economy equilibrium model that simulates the interaction of energy supply demand and the macro-economic performance of key sectors of economy	integrated analysis of broad fiscal policies and technology-specific policies (e.g. GHG reductions resulting from the application of a tax on emissions or change in the vehicle fleet due to a standard on manufacturers sales)	Energy and Materials Research Group, Simon Fraser University	2006	no					

DER-CAM [87], [88]	Distributed Energy Resources Customer Adoption Model	decision support tool that primarily serves the purpose of finding optimal distributed energy resource (DER) investments in the context of either buildings or multi-energy microgrids	find the optimal portfolio, sizing, placement, and dispatch of a wide range of distributed energy resource, while co-optimizing multiple stacked value streams that include load shifting, peak shaving, power export agreements, or participation in ancillary service markets	Lawrence Berkeley National Laboratory	2000	yes	no		yes	electricity, cooling, refrigeration, space heating, water heating, natural gas only	microgrids models
Dhmin [89]	/	mathematical optimisation model for district energy distribution networks	find the minimum cost (invest + operation - revenue) energy distribution network for a given set of energy source locations (source vertices) and a set of demand locations (possible customers)	Renewable and Sustainable Energy Systems, Technical University of Munich	2014	yes	yes	Python	no	heat	demand not organized into sectors
DIETER [90], [91]	Dispatch and Investment Evaluation Tool with Endogenous Renewables	model that determines cost-minimizing combinations of power generation, demand-side management, and storage capacities and their respective dispatch	study the role of power storage and other flexibility options in a greenfield setting with high shares of renewables	German Institute for Economic Research	2015	yes, but purchase GAMS	yes	GAMS	no	electricity	demand not organized into sectors
DIMENSION [92], [93]	Dispatch and Investment Model for European Electricity Markets	long-term simulation model for the European power markets	electricity price forecasts, asset valuation and decision support for investments, strategies for grid expansion and regulation, middle- and long-term scenario analyses	Institute of Energy Economics At the University of Cologne	2011	no					
Dispa-SET [94], [95]	/	open-source unit commitment and optimal dispatch model focused on the balancing and flexibility problems in European grids	service flexibility and adequacy, impact of electric vehicles, RES integration, water-energy nexus	Joint Research Centre, European Commission	2015	yes	yes	Python, GAMS	no	electricity, heat	demand not organized into sectors
dynELMOD [68], [91]	dynamic ELectricity MODel	dynamic partial equilibrium model of the European electricity sector which determines cost-effective development pathways	decide upon investment in conventional and renewable generation and network capacities, calculate the dispatch based on the investment result, or exogenously given capacity scenarios	German Institute for Economic Research	2017	yes	yes	GAMS	no	electricity	demand not organized into sectors
EGEAS [96]	Electric Generation Expansion Analysis System	modular state-of-the-art generation expansion software package	produce integrated resource plans, evaluate independent power producers, develop avoided costs and environmental compliance plans, and analyse life extension alternatives	Electric Power Research Institute	2014	no					
ELMOD [91], [97], [98]	ELectricity MODel	large-scale welfare maximizing engineering and economic model of the European electricity market	congestion management schemes for the electricity market, renewable sources integration, identification of optimal power plant location	Energy Economics and Public Sector Management, Dresden University of Technology	2006	yes, but purchase GAMS	yes	GAMS	no	electricity: industries, services, households; heat	no more detailed subdivision
EMMA [99]	The European Electricity Market Model	techno-economic model of the integrated North-western European power system	determine optimal or equilibrium yearly generation, transmission and storage capacity, hourly generation and trade, and hourly market-clearing prices for each market area	Potsdam-Institute for Climate Impact Research	2013	yes, but purchase GAMS	yes	GAMS	no	electricity, heat	demand not organized into sectors

EnergyPLAN [100]	Advanced energy system analysis computer model	model that simulates the operation of national energy systems on an hourly basis, including the electricity, heating, cooling, industry and transport sectors	assist the design of national energy planning strategies on the basis of technical and economic analyses of the consequences of different national energy systems and investments	Sustainable Energy Planning Research Group, Aalborg University	2000	yes	no	Delphi Pascal	yes	electricity, heating, cooling, industry and fuel, transport, desalination	coal, oil, Ngas, biomass, hydrogen
EnergyRt [101], [102]	energy systems modeling R-toolbox	package for R to develop Reference Energy System (RES) models and analyse energy-technologies	develop multi-region models with hierarchical time-slices, exogenous and endogenous trade routes, and flexible technologies	Oleg Lugovoy; Vladimir Potashnikov	2016	yes	yes	R & GAMS	no	electricity	demand not organized into sectors
ENPEP-BALANCE [103], [104]	Energy and Power Evaluation Program	matches the demand for energy with available resources and technologies	analysing future energy needs and estimating the associated environmental burdens, developing GHG emissions projections and a GHG mitigation analysis	Argonne National Laboratory	1999	yes	yes	not found	no	solid fuels, oil and oil products, gaseous fuels, electricity and heat: energy sector and industrial processes	iron and steel, non ferrous metals, inorganic chemicals, organic chemicals, non-metallic mineral products, others
ETP [105]	Energy Technology Perspectives	combines analysis of energy supply and demand, supporting integration and manipulation of data from four soft-linked models: energy conversion, industry, transport, buildings	IEA's Energy Technology Perspectives: identify an economical way for society to reach the desired outcome	International Energy Agency	2016	no		TIMES - based			
EUCAD [106], [107]	European Unit Commitment And Dispatch	unit commitment model that computes the balance between supply and demand at the hourly time-step for all European countries at once	minimisation of the total European power system operation cost	Université Grenoble Alpes	2015	no		GAMS			
Ficus [108], [109]	/	a (mixed integer) linear optimisation model for local energy systems	find the minimum cost energy system to satisfy given demand time-series for possibly multiple commodities	Institute for Energy Economy and Application Technology, Technische Universität München	2015	yes	yes	Python	no	can create any custom demand	can be created
FORECAST [110]	FORecasting Energy Consumption Analysis and Simulation Tool	develops scenarios for the long-term development of energy demand and greenhouse gas emissions for the industry, services and household sectors	study energy efficiency potentials and costs in materials industries, produce long-term climate policy scenarios	Fraunhofer Institute for Systems and Innovation Research; TEP Energy; IREES	2007	no		finished projects sold (Visual Basic.NET)			
GEM-E3 [111]	General Equilibrium Model for Energy-Economy-Environment	recursive dynamic computable general equilibrium model that covers the interactions between the economy, the energy system and the environment	evaluate climate and energy policies, as well as fiscal issues. Used in European Commission studies	E3MLab/ICCS of NTUA; JRC-IPTS; others	2011	no		GAMS			
GENESYS [112], [113]	Genetic Optimisation of a European Energy Supply System	program which optimizes a future European power system with high shares of renewable energy sources	optimize the allocation and size of different generation technologies, storage systems and transnational grids of a European power system	RWTH Aachen University	2016	yes	no	C++	no	electricity	demand not organized into sectors

GTAP-E [114], [115]	Global Trade Analysis Project - Energy	multiregion, multisector, computable general equilibrium model, with perfect competition and constant returns to scale	environmental and energy research, GHG emissions, land use, bio-fuels	College of Agriculture, Purdue University	1994	yes	yes	Gempack	RunGTAP	agriculture, forestry and fishing; coal; crude oil; gas; refined oil products; electricity; ferrous metals; chemical, rubber, plastic products; other manufacturing; trade and transport; commercial/public services, dwellings	refined oil products; ferrous metals; chemical, rubber, plastic products; other manufacturing
HOMER [116], [117]	Hybrid Optimization of Multiple Energy Resources	distributed generation and microgrid modelling software	optimizing microgrids and distributed energy resources	HOMER Energy LLC	1993	no		executable			
INTRES [118]	INTegrative model approach on Renewable Energy Sources	/	doctoral thesis "A cost-efficient expansion of renewable energy sources in the European electricity system – an integrated modelling approach with a particular emphasis on diurnal and seasonal patterns"	Christiane Golling, Institute of Energy Economics at the University of Cologne	2011	no					
LEAP [119]–[121]	Long-range Energy Alternatives Planning	tracks energy consumption, production and resource extraction	user friendly analysis for national energy-systems	Stockholm Environment Institute	1980	for students and developing countries	yes	Visual Basic	yes	electricity and heat: household, industry, transport, commercial	iron and steel, pulp and paper, electricity, residual fuel oil
LIMES [122]	Long-term Investment Model for the Electricity Sector	linear optimization modelling framework that determines cost-minimizing investment and dispatch decisions for generation, storage and transmission technologies	long-term assessment of integration of fluctuating RES into power sector under climate constraints	Potsdam Institute for Climate Impact Research	2011	no		GAMS			
MARKAL [123], [124]	MARKet ALlocation model	energy–economic tools for national energy-systems	used for European Commission 20-20-20 targets	Energy Technology Systems Analysis Program, IEA	1978/2004	no		GAMS + solver			
MATPOWER [125]	/	package of free, open-source Matlab-language M-files for solving steady-state power system simulation and optimization problems	research and education related to the economic, environmental and engineering aspects of electric power grids	Power Systems Engineering Research Center, Cornell University	1997	yes	yes	Matlab/ Octave	no	AC/DC loads	electric power flow model
MESSAGE [126]–[129]	Model for Energy Supply Strategy Alternatives and their General Environmental impact	systems engineering optimization tool	national or global energy-systems in medium/long-term (used for IPCC and World Energy Council)	International Institute for Applied Systems Analysis	1980s	for academic purposes and IAEA states, but simulators must be purchased	no	GAMS and Oracle	web interface for data and results visualization: data.ene.iiasa.ac.at/iamc-1.5c-explorer	electricity, liquid fuels, solid fuels, gaseous fuels, soft solar, heat I (from central sources), heat II (from small suppliers), renewables	can be created
MESSAGEix [130], [131]	"	versatile, dynamic systems-optimization modelling framework	analyse scenarios of the energy system transformation under technical-engineering constraints and political-societal considerations	International Institute for Applied Systems Analysis	1980s	yes	yes	Python	no	transport, residential/commercial, industry	feedstock, thermal and specific demand (electricity or conversion to electricity)

Minpower [132]	/	open source toolkit for power systems optimization	calculation of Economic Dispatch, Optimal Power Flow, Unit Commitment in a power system	Adam Greenhall	2012	yes	yes	Python	no	AC/DC loads	electric power flow model
MOST [133]	MATPOWER Optimal Scheduling Tool	MATPOWER framework for solving generalized steady-state electric power scheduling problems	stochastic, security-constrained, combined unit-commitment and multiperiod optimal power flow problems with locational contingency and load-following reserves, ramping costs and constraints, deferrable demands, lossy storage resources and uncertain renewable generation	Power Systems Engineering Research Center, Cornell University	2016	yes	yes	Matlab/ Octave	no	AC/DC loads	electric power flow model
MUSE [134]–[136]	ModUlar energy systems Simulation Environment	provides a global whole systems perspective on opportunities and challenges for the energy industry	following a simulation approach coupled with an imperfect foresight, models the real-world decision making of investors realistically	Sustainable Gas Institute, Imperial College London	currently under development	will be	will be	Python	no (simulator: museenergysimulator.co.uk)	residential; commercial; transport; industry; agriculture	chemicals; iron; non-ferrous metals; non-metallic minerals; pulp and paper; steel. Further subdivision into detailed sectors
NEMO [137]–[139]	National Electricity Market Optimiser	high-performance, open-source energy system optimization tool	capacity expansion and power development planning, energy strategies, energy-water-food nexus analyses, and deep decarbonization studies	Stockholm Environment Institute	2011	yes	yes	Python	LEAP	electricity and heat: household, industry, transport, commercial	iron and steel, pulp and paper, electricity, residual fuel oil
NEMS [140]–[143]	National Energy Modelling System	simulates the US energy market economics, industry structure and existing energy policies and regulations	US Annual Energy Outlook	US Department of Energy	1993	yes, but simulators must be purchased	on request	Fortran 90	no	residential; commercial; transportation; industrial	combined heat and power; 7 energy-intensive industries; 8 non-energy-intensive; 6 non-manufacturing. Further subdivision for detailed process flows
Oemof [144]–[146]	Open Energy MOdelling Framework	organisational frame for tools in the wide field of (energy) system modelling	planning and evaluation of district energy systems, decision-making for distributed energy systems, studies about storage or district heating	Reiner Lemoine Institut	2015	Yes	yes	Python	no	electricity, heat	can be created
OnSSET [147], [148]	OpeN Source Spatial Electrification Tool	bottom up optimization energy modelling tool, that estimates, analyses and visualizes the most cost effective electrification strategy	provide invaluable support to policy and decision makers on least-cost electrification strategies	KTH Royal Institute of Technology	2015	Yes	yes	Python	QGIS or any GIS software	electricity: residential	residential only
OSeMOSYS [71], [72], [149]–[151]	Open Source energy MOdeling SYStem	modelling framework for the long-range optimisation of the energy system and energy mix of user-defined regions	projects with detailed energy systems and integrated assessment models of several countries in different continents	KTH Royal Institute of Technology	2008	Yes	yes	GAMS, Python	MoManI, LEAP	can create any custom demand as FUEL	can be created as TECHNOLOGY
Pandapower [152], [153]	/	easy to use open source tool for power system modelling, analysis and optimization with a high degree of automation	static analysis of balanced power systems: transmission and subtransmission systems (typically operated symmetrically) and symmetric distribution systems	Energy Management and Power System Operation, University of Kassel; Grid Planning and Grid Operation Division, Fraunhofer Institute for Energy Economics and Energy System Technology	2016	Yes	yes	Python	no	AC/DC loads	electric power flow model

PERSEUS [154]	/	energy and material flow model applying a multi-periodic linear programming approach	analyse benefits of international mechanisms against climate change, effects of the emissions trading scheme on European electricity sector…	Institute for Industrial Production, Universitat Karlsruhe	1999	no, sold to large European utilities					
PLEXOS [155]	/	fast, sophisticated, easy to use and cost-effective market simulation software to provide a high-performance, robust simulation system for electric power, water and gas markets	long-term capacity expansion planning, power generation, transmission modelling, reliability studies, renewable energy integration, energy storage, multi-stage stochastic hydro optimization, ancillary services, dispatch optimization, market analysis, risk analysis, market design, maintenance planning, hydro-thermal coordination, competition modelling, gas and LNG studies	Energy Exemplar	2000	for academic institutions for non-commercial research. Costs for supported solvers	no		yes	not found	not found
POLES [156]	Prospective Outlook on Long-term Energy Systems	global energy model that covers the entire energy balance, from final energy demand, transformation and power production to primary supply and trade of energy commodities	Global Energy and Climate Outlook	Joint Research Centre, European Commission	1990s	no					
POTEnCIA [157], [158]	Policy Oriented Tool for Energy and Climate change Impact Assessment	modelling tool that allows for a robust assessment of the impact of different policy futures on the EU energy system	represent the economically driven operation of the European energy markets and the corresponding interactions of supply and demand	Joint Research Centre, European Commission	2016	no					
PRIMES [159]	Price-Induced Market Equilibrium System	simulates a market equilibrium solution for energy supply and demand: engineering + economics	produce energy outlooks, scenario construction and impact assessment of energy and climate policies	E3MLab/ICCS of National Technical University of Athens	1994	not sold, projects completed for a fee					
Psst [160]	Power System Simulation Tool	open-source Python application for the simulation and analysis of power system models	simulates the wholesale market operation, with the ability to let researchers understand the effect of modelling methodologies or network representations	Advanced Research Projects Agency-Energy; Iowa State University	2016	yes	yes	Python	no	AC/DC loads	electric power flow model
PyOnSSET [161]	Python OnSSET	Python implementation of the OpeN Source Spatial Electrification Toolkit	/	division of Energy Systems Analysis, KTH Royal Institute of Technology	2016	yes	yes	Python	no	electricity: residential	residential only
pyPSA [162], [163]	Python for Power System Analysis	free software toolbox for simulating and optimising modern power systems	calculate static power flow, linear optimal power flow, security-constrained linear optimal power flow, total electricity/energy system least-cost investment optimisation	Frankfurt Institute for Advanced Studies	2016	yes	yes	Python	no	can create any custom demand	can be created

ReEDS [164], [165]	Regional Energy Deployment System	simulates the evolution of the bulk power system - generation and transmission - from present day through 2050 or later	inform a wide range of electricity sector research questions such as clean energy policy, renewable energy integration, technology innovation, and other forward-looking generation and transmission infrastructure issues	National Renewable Energy Laboratory, USA	2011	yes, but purchase GAMS	yes	GAMS, Python, R	no - results viewer: openei.org/apps/reeds	electricity	demand not organized into sectors
REnPaSS [166]	Renewable Energy Pathways Simulation System	simulates the electricity supply and use of infrastructure	fulfil the requirements of full transparency and the possibility to image 100% renewable energy systems as well as today's system on a high regional and time resolution	Centre for Sustainable Energy Systems, University of Flensburg	2014	yes	yes	R	no	electricity [heat and transport in future versions]	can be created
RETScreen [167], [168]	Renewable-energy and Energy-efficient Technologies Screen	clean energy management software system for energy efficiency, renewable energy and cogeneration project feasibility analysis as well as ongoing energy performance analysis	evaluate the energy production and savings, costs, emission reductions, financial viability and risk for various types of Renewable-energy and Energy-efficient Technologies (RETs)	Government, Industry and Academia by Natural Resources Canada	1996	no (viewer mode only)	no		RETScreen Expert	power plant; power, heating, cooling; industrial; commercial/institutional; residential; agricultural; individual measure; transportation; other	very detailed: more than 60 industrial sub-sectors
Rivus [169], [170]	/	mixed integer linear optimisation model for energy infrastructure networks	find the minimum cost energy infrastructure networks to satisfy a given energy distribution for possibly multiple commodities	Renewable and Sustainable Energy Systems, Technical University of Munich	2016	yes	yes	Python	no	electricity, heat	can be created as building demand
Switch [171]	Solar, WInd, Transmission, Conventional generation and Hydroelectricity	capacity expansion model that invests in new generation and transmission assets as well as in end-use and demand-side management options	explore energy choices across the US West (the WECC, Chile, Nicaragua, China), with future plans to cover the East African Power Pool (EAPP) and India	Renewable & Appropriate Energy Laboratory, UC Berkeley	2015	yes	yes	Python	no	electricity (at load zone level)	demand not organized into sectors
TEMOA [172]	Tools for Energy Model Optimisation and Analysis	open source modelling framework for conducting energy system analysis	derive policy-relevant insight related to the cost, emissions, deployment, and coordinated operation of energy technologies over time while rigorously accounting for large future uncertainties	North Carolina State University	2012	yes	yes	Python	model.temoacloud.com	can create any custom demand as commodity	can be created as technology
THEA [173]	The High temporal resolution Electricity-market Analysis-model	linear optimization dispatch and investment model	quantify differences in investment decisions through an investment and dispatch power system model	Lawrence Berkeley National Laboratory	2010	no					
TIMES [124], [174]	The Integrated MARKAL-EFOM System	technology rich, bottom-up model generator, which uses linear-programming to produce a least-cost energy system	exploration of possible energy futures based on contrasted scenarios	Energy Technology Systems Analysis Program, IEA	2004	no		GAMS			
URBS-EU [175]	/	linear optimization model for distributed energy systems	determine cost-optimal grid extensions to integrate VREs, investigate the role of the grid for electricity markets and their participants	Renewable and Sustainable Energy Systems, Technical University of Munich	2014	yes	yes	Python	no	can create any custom demand as commodity	can be created as commodity

US-REGEN [176]	US Regional Economy, Greenhouse gas, and ENergy model	model that combines a detailed dispatch and capacity expansion model of the electric sector with a high-level dynamic computable general equilibrium (CGE) model of the economy	model a wide range of environmental and energy policies in both the electric and non-electric sectors	Electric Power Research Institute	2011	no					
WASP-IV [177]–[179]	Wien Automatic System Planning package	model that determines the optimal long-term expansion plan for a power generating system	evaluate the potential of biomass power generation, the role of nuclear power or a country's dependence on imported fuels	International Atomic Energy Agency	1972	for IAEA member states	no	(MS DOS environment)	no	electricity	demand not organized into sectors
WEM [180]	World Energy Model	large-scale simulation model designed to replicate how energy markets function	generate detailed sector-by-sector and region-by-region projections for the World Energy Outlook scenarios	International Energy Agency	1993	no					

Table 24 – energy models review

For each model considered, in Table 24 are indicated its acronym, together with associated references, name with a short description, some examples of typical applications, the name of the company, institution or organization that created it (that usually maintains it and provides it, too), the year of first release and whether it is for free or not: the necessity of purchasing additional components to be run is also specified. Models that result for free are further analysed, reaching a deeper level of detail.

As previously assessed, for transparency's sake it is important that a model is publicly accessible in the form of both source code and data, allowing users to manipulate it at their will. Regarding what users can do with any generic open source software, GNU defined in 1984 four requirements for a software to be called *free*: "the freedom to run the program, for any purpose; the freedom to study how the program works, and change it to make it do what you wish; the freedom to redistribute copies so you can help your neighbour; the freedom to distribute copies of your modified versions to others." In this sense *free software* refers to permissions associated to it, not only to its monetary price. [73]
Since, as said, there is a substantial difference between *free of charge* and *open source*, free models listed in Table 24 have been inspected to verify if their source code is effectively available (in most cases it can be found online in repositories such as GitHub). If the code is accessible, its programming language is specified. Then, the existence of a user-friendly interface is highlighted, for the case in which who is dealing with the model doesn't have experience in programming.

Bringing the focus back to open-source models (both with and without available source code), their structure on the demand side is examined. The "*Demand included"* column provides the list of energy carriers considered in the model that can be set as input data: the most frequent are electricity and heat. If available, the sectors in which demand is divided are also specified at the same place, for example: residential, industrial, transports… Those indicated with "*can create any custom demand"* imply that the model doesn't have a predefined structure, but the user is free to build an energy system with the characteristics that better fit his subject of analysis. The specific name of demand may be citated (e.g., "*as fuel"*). Anywhere there is "*not found",* it simply stands for: this information was not retrieved.

For the purpose of this thesis, we are in particular interested in those models that comprise industrial sector as a final energy consumer, so the label "*Industry"* indicates how industrial demand is designed within the modelling tool and which industrial subsectors are there conceived. A rough classification by colour points out whether each model is suitable for an application in the industrial field or not.
Let's first analyse the ones with non-satisfying features, distinguished with red colour. Models whose only demand is indicated as "*AC/DC loads"* are intended to be used to model power systems composed by electric components and perform power flow problems, rather than representing an entire energy system of a whole region, such as a country, where industries operate. A similar reason applies to DER-CAM and OnSSET, that were created to be applied respectively in microgrids and residential systems. At last there are a bunch of models whose energy demand is not accurately organized, so it's not possible to distinguish how much energy will serve industrial sector of the total final consumption, since it is a unique data.
Yellow lines mean that the industrial sector is not specifically present yet, but it can be included since the model allows a free construction of commodities, including final demand sectors: if there is a particular name for them, it is explicated.
Finally, models in green were judged to be appropriate for an industrial energy analysis. They can provide a generic industrial demand, not further detailed, or they can include a more exhaustive subdivision by production branches, by fuel type, by demand type… Some of them go so deep into detail that the entire list of industrial subsectors couldn't fit in the table: we're talking about NEMS and RETScreen.

The industrial demand module of NEMS is reported in Table 25:

Energy-intensive manufacturing	**Non-energy-intensive manufacturing**	**Non-manufacturing**
Food products	Metal-based durables industries	Agricultural crop production
Paper and allied products	Fabricated metal products	Other agricultural production
Bulk chemicals	Machinery	Coal mining
Inorganic chemicals	Computer and electronic products	Oil and natural gas extraction
Organic chemicals	Electrical equipment and appliances	Metal and other nonmetallic mining
Resins	Transportation equipment	Construction
Agricultural chemicals	Wood products	
Glass and glass products	Plastic and rubber products	
Cement and lime	Balance of manufacturing	
Iron and steel		
Aluminum		

Table 25 – NEMS industrial demand module

Figure 10 instead lists all the industrial subsectors that are included in RETScreen. It is extremely detailed, and it is intended to model a single facility rather than an entire system.

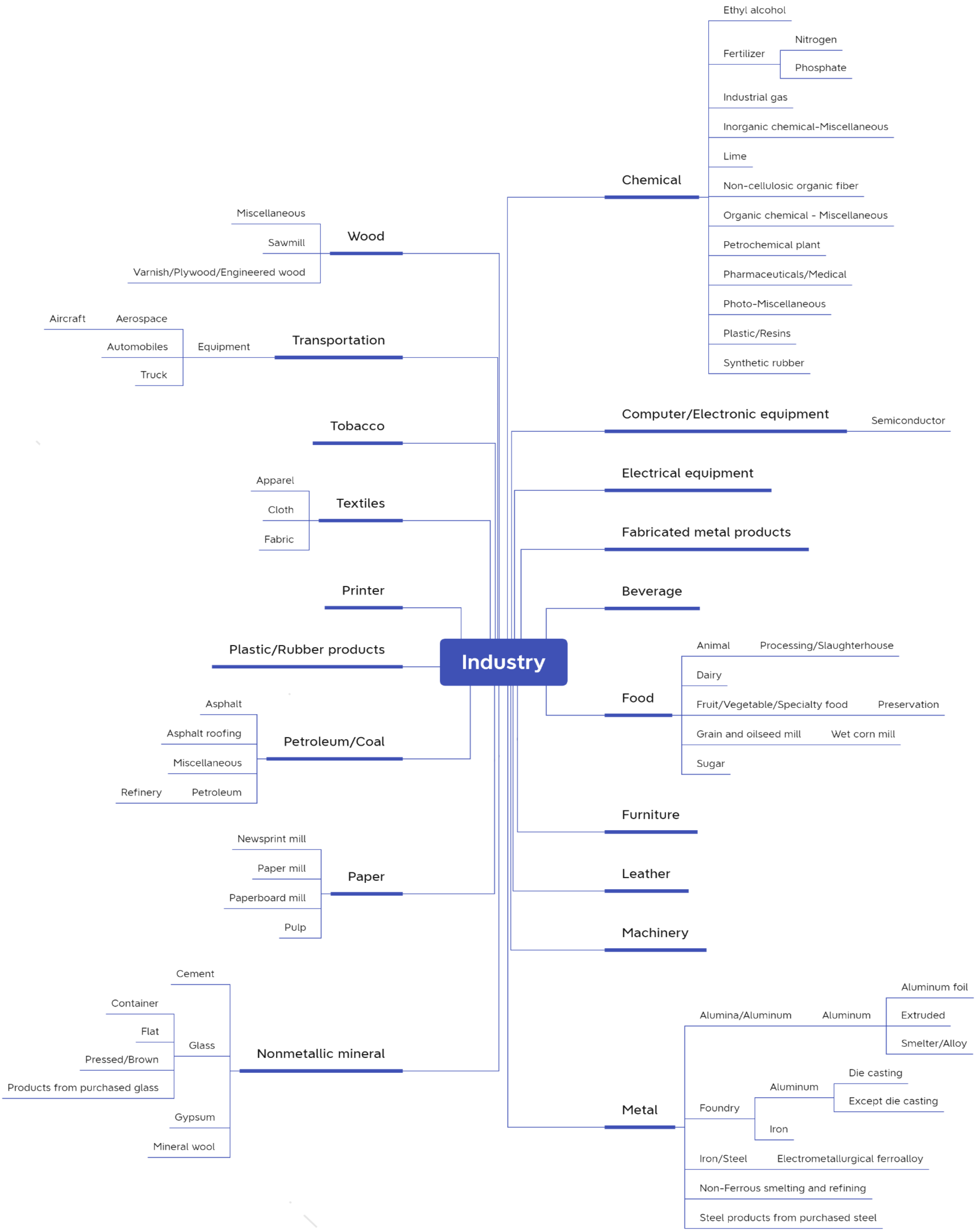

Figure 10 – RETScreen industrial sectors

Chapter 5 – Case study

Location

The distillery is located in the surroundings of Rothes, in Scotland, UK, in the whisky production region of Speyside. Weather and other geographical data about sun, wind and temperature are reported by Homer Pro from NASA databases POWER.

Production capacity

According to Bell's classification, small, independent traditional distilleries that sell in local markets have a production of less than 1 million litres of pure alcohol per year, while big corporations for international brands typically produce more than 30 million litres per year [14]. Here a middle-scale distillery is considered, with a production capacity of 2 million litres of whisky per year. Considering a bottle size of 0,7 litres (the most diffused for alcoholic beverage [3]), this would mean that about 2,86 million bottles are manufactured each year.

Demand

Demand subdivision

According to a report by Scotch Whisky Association [181] based on the data from a total of 127 between distilleries and packaging sites, the fuel consumption of this kind of plants is for most headed to heat applications (82,7%), while only the remaining 17,3% is used in form of electricity. In Figure 11 also a further subdivision into sectors of utilization can be seen for the heat part of consumption. It is noticeable that distillation process is the more energy intensive among all, accounting for 91% of heat usage, while only 1% is employed in buildings space heating or other applications requiring hot water at a relatively low temperature. Industrial processes different from distillation, for example malting step, consume 6% of energy, corresponding to 8% of total heat.

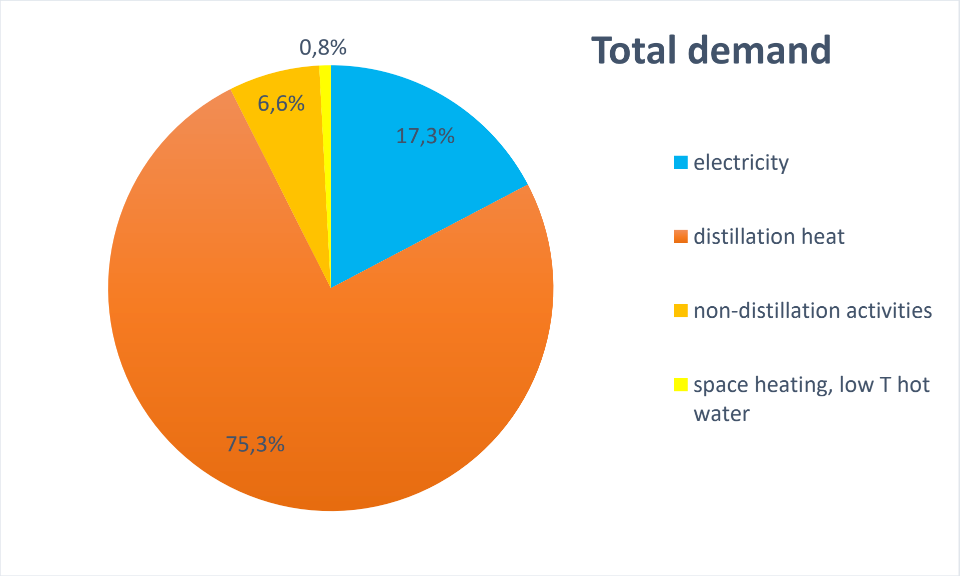

Figure 11 – sector subdivision of demand

A research conducted at the Strathclyde University in Glasgow [43] reveals that for every litre of whisky produced, 6,29 kWh are consumed for distilling and maturation phases, while its packaging requires 0,37 kWh per litre, that is only 5,6% of total as highlighted in Figure 12.

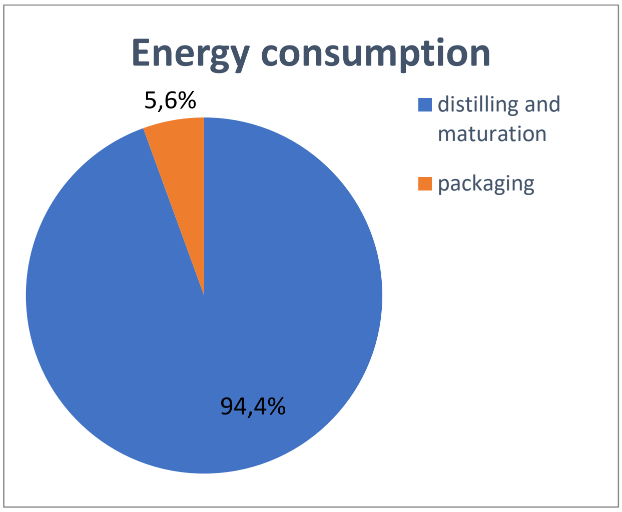

Figure 12 – energy consumption

Considering heat energy only, the consumption for the production of whisky is split according to Figure 13. Going more into details, a distillery's steam usage is made mostly for distillation (about 90%), while the remaining 10% is consumed by mashing stage. [182]

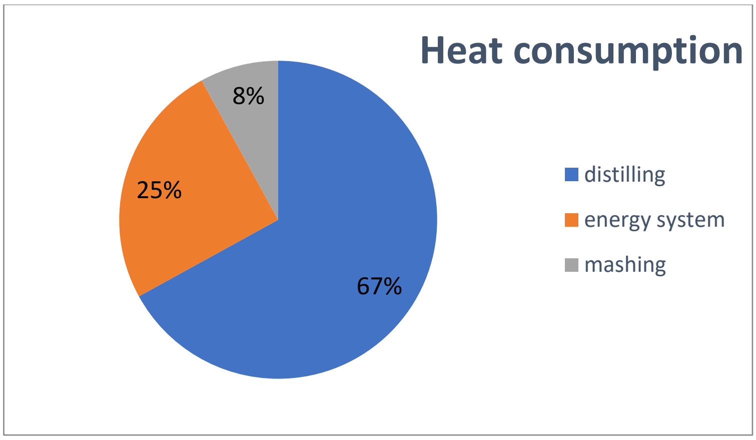

Figure 13 – heat consumption

These considerations do not include auxiliary utilities such as space heating, lighting and so on; that's why these data don't match, for example, with a survey conducted by the Scottish Craft Distillers Association (SCDA) [183], that reveals a specific energy consumption range of 12,7÷13,9 kWh per litre of Whisky.
An accurate life cycle sustainability assessment individuated the contribution of each life cycle stage of Scotch whisky to the environmental impact, in particular in terms of primary energy demand, as indicated in Figure 14 [4].

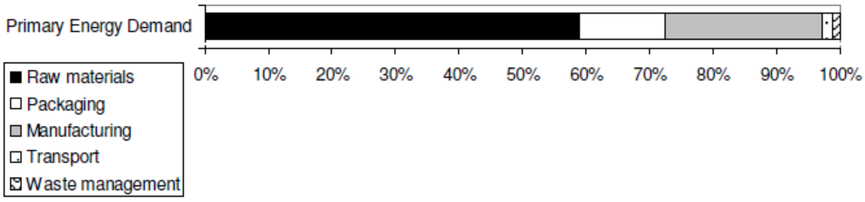

Figure 14 – primary energy demand contribution

Demand calculation

Due to previously mentioned omissions and other simplifications, the total demand of 6,66 kWh per litre of whisky produced results to be an underestimation with respect to reality, proved by the fact that consumption data provided by a bunch of real plants in Scotland are higher than that: they vary from 7,3 to 13,5 kWh/l, with an average value around 9,4 kWh per litre [43]. These data can be linearized into an empirical correlation that approximates quite well their global trend:

$$\boldsymbol{total\ demand\ \left[\frac{kWh}{y}\right] = whisky\ production\ \left[\frac{l}{y}\right] * 8,5 + 1,5 * 10^5}$$

Applying the same methodology to specific data regarding electrical and thermal consumption with respect to whisky production, the following formulas for a preliminary estimation are obtained:

$$\boldsymbol{heat\ demand\ \left[\frac{kWh}{y}\right] = whisky\ production\ \left[\frac{l}{y}\right] * 8,0 +\ 1,57 * 10^5}$$

$$\boldsymbol{electricity\ demand\ \left[\frac{kWh}{y}\right] = whisky\ production\ \left[\frac{l}{y}\right] * 0,35 + 7 * 10^3}$$

Corresponding average heat demand is 9,19 kWh per each litre of whisky produced, while electric demand is 0,40 kWh/l.

Figure 15, Figure 16 and Figure 17 show how linear empirical correlations fit with trends coming from real plants data. Red dots indicate the resulting value of respectively total, heat and electricity demand calculated with the three formulas above for the distillery with a production capacity of 2 million litres per year.

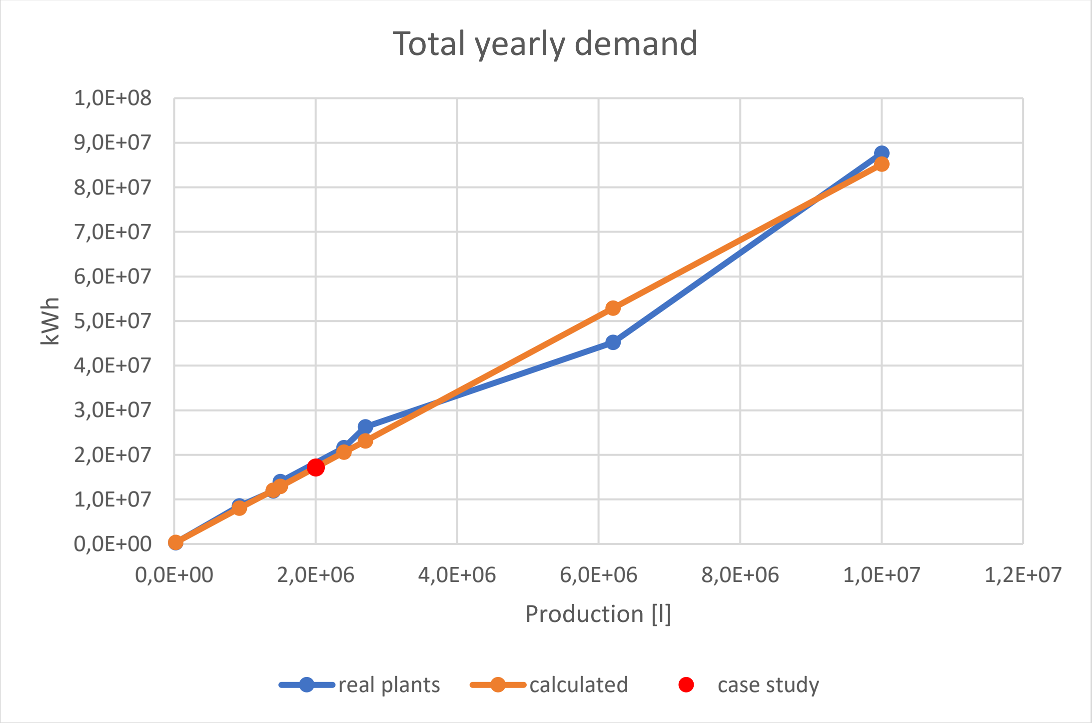

Figure 15 – total demand

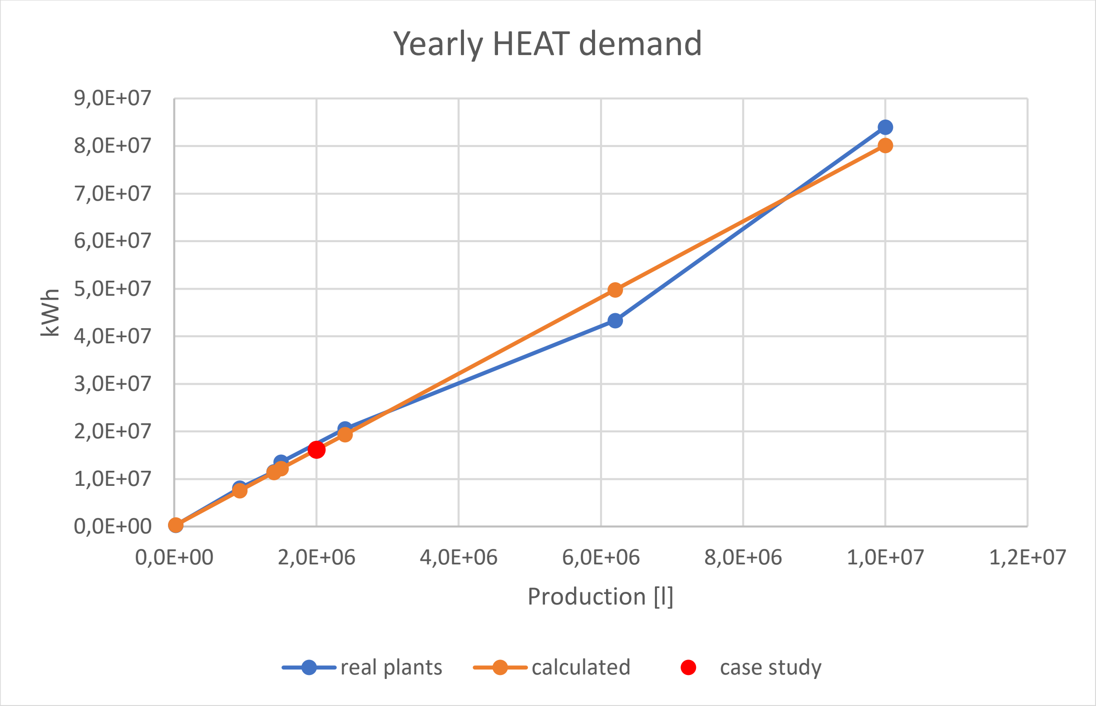

Figure 16 – heat demand

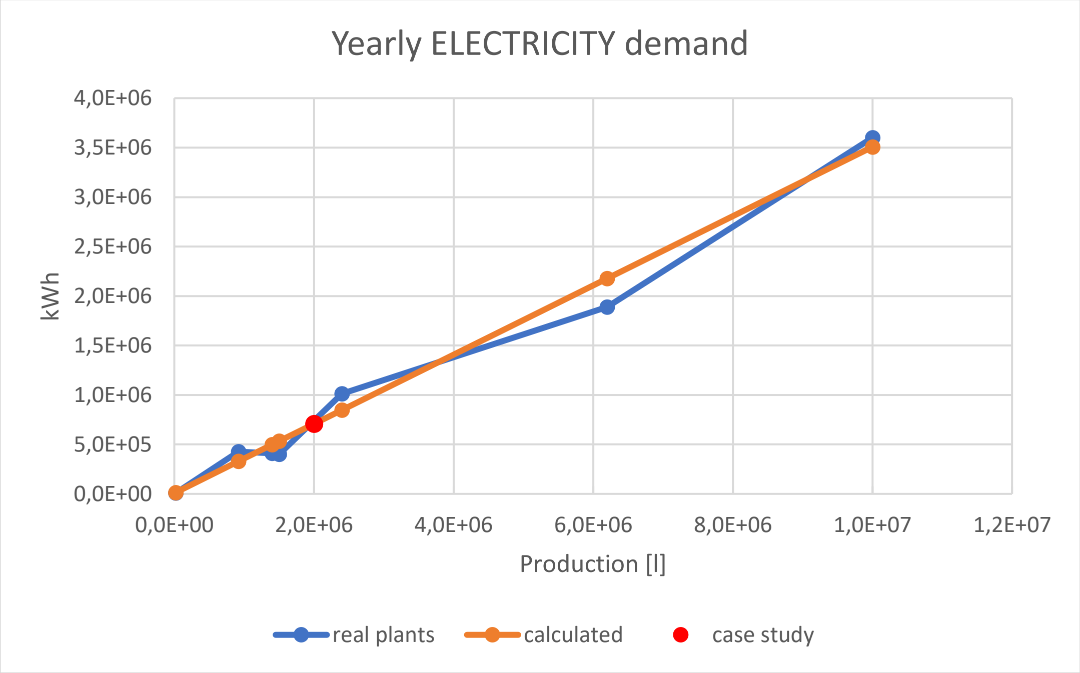

Figure 17 – electricity demand

Table 26 sums up the resulting values for the case study, on an annual basis, in MWh. For consistency, from now on the total demand value will be calculated just as the sum of the two components (heat and electricity).

Production [l/y]	Heat demand [MWh/y]	Electricity demand [MWh/y]	Total demand [MWh/y]
2.000.000	16.157	707	16.864

Table 26 – yearly demand overview

Specific values for the case study of demand in correlation with each litre of whisky produced are indicated in Table 27. They perfectly resemble data in literature [17].

Production [l/y]	Heat demand [kWh/l]	Electricity demand [kWh/l]	Total demand [kWh/l]
2.000.000	8,08	0,35	8,43

Table 27 – demand per litre of whisky

Figure 18 highlights the difference between electric and thermal demand in the case study.

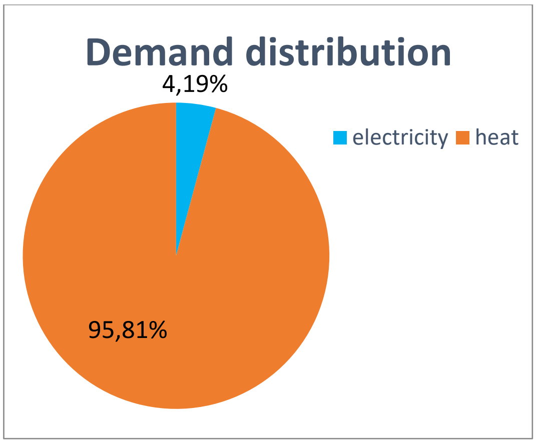

Figure 18 – demand distribution

Demand profile and load factor

The demand profile of distilleries can be different from one another, according to their own design, process, operation times and other variables. As an example, Figure 19 shows thermal and electrical demand profile of a whisky distillery with a production capacity of about 2,5 million litres of whisky per year. In Figure 19 a time range of one week (from Monday to Sunday) is plotted, using one-hour steps, considering that the plant works 6 hours per day (from 10:00 to 16:00), 5 days a week, for 49 weeks in one year (3 weeks of closure are assumed); seasonal variations in this profile are not included for simplicity, although higher heating and lighting would be needed during winter. As it can be seen, peaks of 1 MW and 3,6 MW are reached respectively for electrical and thermal load, while minimum electric consumption is 0,3 MW. [46]

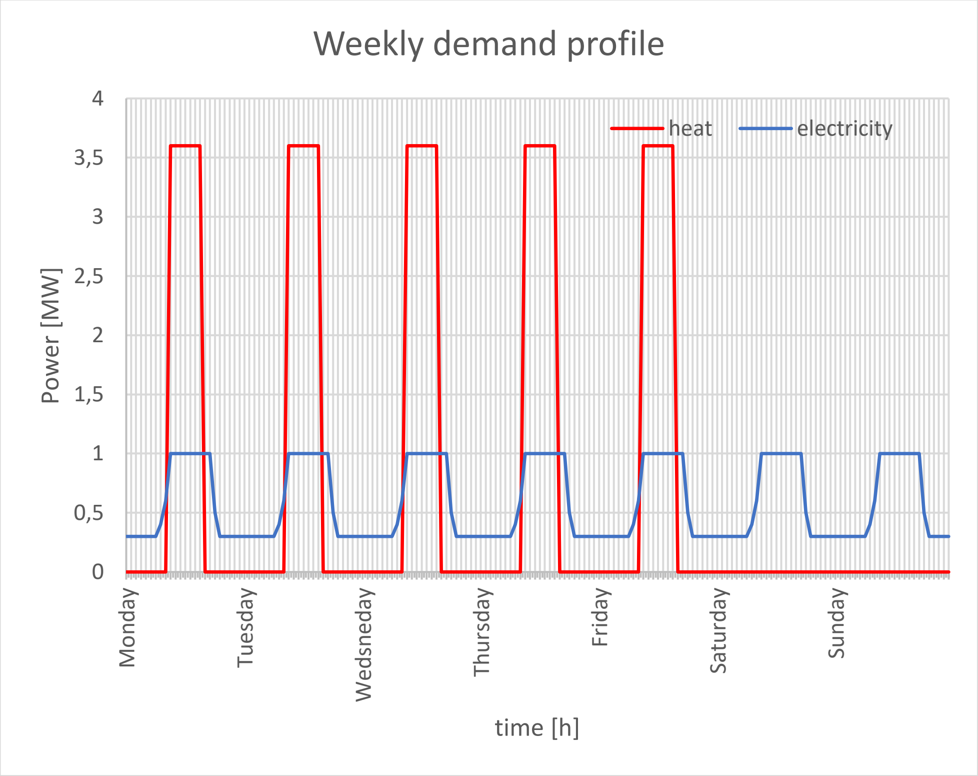

Figure 19 – sample demand profile

From these data, a load factor on a yearly basis can be extracted, resulting in a load factor of 50,9% for the electricity share of consumption and a load factor of 16,8% for the heat part.

However, a real distillery in the Speyside has a yearly thermal load of 18,000 MWh that is completely supplied by a 4 MW biomass boiler, meaning that the plant works at a thermal load factor of 51,4%. [184] Considering that the value cannot be higher than 1, it was concluded that the distillery operation time was 24 hours per day, for 7 days a week, with no scheduled closures, that is consistent with job offers in the distilling sector. The value of 51,4% is slightly lower than the mean value (that is 68%) resulting from generic typical values of load factor for industrial sector of food manufacturing identified in a thesis study [185], but still in line with them.

For this study the overall load factor is rounded to the value of 51%, resulting in a synthetic profile with peak load of 158,25 $kW_{electric}$ and 3616,48 $kW_{thermal}$, according to the definition of load factor:

$$Load\ factor = \frac{total\ demand\ [kWh]}{peak\ load\ [kW] * total\ time\ [h]}$$

That profile has been created roughly following a typical daily (with hourly timesteps) demand curve of a generic industrial customer, expressed in percentage of peak load [186]. It is reported in Figure 20, that shows both electric and thermal load for the case study. No seasonal variations nor differences between weekdays and weekends are introduced. Same considerations are made for both electricity and heat.

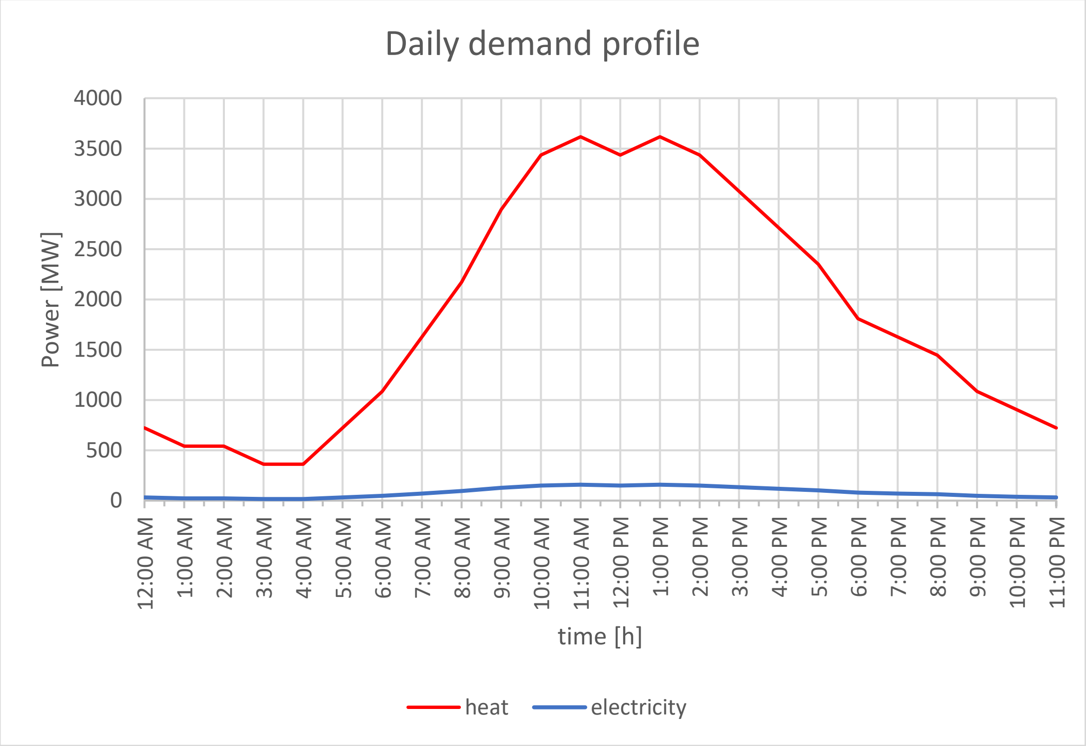

Figure 20 – case study demand profile

Table 28 sums up main data of case study demand profile distribution:

Load factor [%]	Heat peak [kW]	Heat min demand [kW]	Electricity peak [kW]	Electricity min demand [kW]	Operating hours	Operating days	Seasonal variations
51	3616,48	361,65	158,25	15,83	24/24	7/7	no

Table 28 – case study demand distribution

Electrical Design

Grid

The distillery plant is supposed to be linked to national grid, both for electricity and natural gas supply. Grid power price is established to be 0,1502 £ per kWh (rounded to 0,150 for calculations) including the Climate Change Levy, as it is the tariff for small/medium manufacturing industry purchasing in the range from 500 to 2.000 MWh/y published by UK government and based upon data from Office for National Statistics, updated to the third quarter of 2021 [187]. The sellback price is instead based on a comparison between different suppliers' offers: 0,055 £/kWh [188]. Electricity generation mix in UK is composed by 63% non-renewable and 37% renewable energy sources [189]. Basing on data by United States Environmental Protection Agency [190], emission rates for electrical grid are set as in Table 29, that sums up also grid prices for electricity, both purchased and sold.

Electricity prices		**Grid emissions**		
Purchasing price [£/kWh]	**Sellback price [£/kWh]**	**CO_2 [g/kWh]**	**SO_2 [g/kWh]**	**NO_x [g/kWh]**
0,150	0,055	512,13	0,097	0,24

Table 29 – grid properties

PV system

A solar photovoltaic system is introduced in the plant for the production of electricity. Basing on the best available technology criterion, a commercial PV panel by SunPower is chosen, since it is the one with higher efficiency among the HOMER library that corresponds to characteristics looked for. In Table 30 data sheet of the module is reported:

Name	**Capacity [kW]**	**Derating factor [%]**	**Lifetime [years]**	**T effect on power [%/°C]**	**NOCT [°C]**	**Efficiency [%]**
SunPower X21-335-BLK	0,335	88	25	-0.3	43	21

Table 30 – PV module properties

The capital cost for photovoltaic system in UK is 1.160 £/kW, according to Irena's 2021 report [191]. This price is the total cost for commercial installations in 2020, including all components such as module price, that is around an average of 216 £/kW, inverter cost (assumed to be between 30 and 34 £/kW), racking and mounting, grid connection, cabling/wiring, safety and security, monitoring and control, mechanical and electrical installation, inspection, margin, financing costs, system design, permitting and so on…

Operation & Maintenance costs are set to be 8 £/kW per year [191]. All prices in US dollars are converted in British pounds following the ratio of 0,75 £/$.

Converter

For simulation purposes, a generic inverter working in parallel with AC grid that has a very large size is selected, so that Homer calculator can size the entire system without concerning about inverter size. Inverter costs are included into global costs of PV system, without specifying each component's contribution, and its properties are listed in Table 31.

Name	**Capacity [kW]**	**Inverter efficiency [%]**	**Rectifier efficiency [%]**	**Rectifier relative capacity [%]**	**Lifetime [years]**
Generic large, free converter	9999999	95	95	100	15

Table 31 – inverter properties

Battery

Since electricity selling price is by far lower (37%) than purchasing cost, introducing a battery storage in the system should be convenient in economical terms, because it increases electricity self-consumption instead of energy market trading, that is a disadvantage for users.

A series of commercial lithium-ion batteries, with characteristics listed in Table 32, is added to the model.

Model	Nominal capacity [kWh]	Maximum capacity [Ah]	Initial state of charge [%]	Minimum state of charge [%]	Lifetime [y]
SAFT Intensium Max plus 20M ESSU	55,03	76,4	100	10	20

Table 32 – battery properties

Capital cost of residential and commercial Li-ion batteries updated to 2021 [191] is 564,09£/kWh and operational cost is 8 £/kWh/y, resulting respectively in 31.025,2 £ and 412,5 £/y per unit.

Results and comments

Configuration 1 – Base case

The base case to be taken as a reference for the subsequent improvements is composed uniquely by the distillery and the electrical grid, from which it buys all needed electrical energy. Table 33 sums up main data.

Grid purchases [kWh/y]	Grid sales [kWh/y]	Renewable penetration[16] [%]	CO_2 emissions [kg/y]
707.585	0	0	447.194

Table 33 – base case results

Note[16]: Homer software includes emissions due to electricity generation for the grid, but it does not consider the national energetic mix when calculating renewable penetration. For this reason, in every configuration the renewable fraction is referred to energy produced in the plant itself, while renewable energy sources used to form the total energy mix in the grid are to be considered separately.

Configuration 2 – Photovoltaic only

The more obvious change in order to decrease carbon emissions is increasing renewable energy through the installation of a photovoltaic plant on the distillery's property. Figure 21 summarises the configuration with photovoltaic only and main fluxes of electric energy.

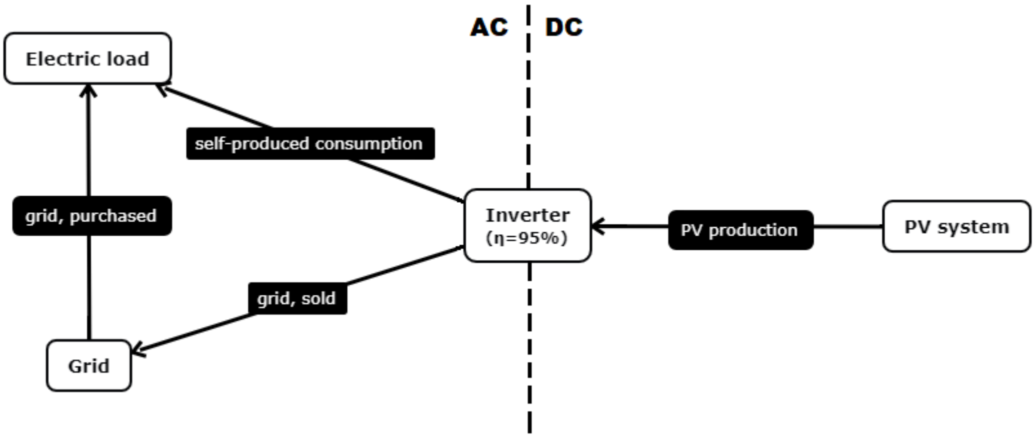

Figure 21 – PV only configuration

Table 34 reports yearly data resulting from simulation of configuration with photovoltaic plant:

PV capacity [kW]	**PV production [kWh/y]**	**Grid purchases [kWh/y]**	**Grid sales [kWh/y]**	**Renewable penetration[16] [%]**	**CO_2 emissions [kg/y]**
272,67	257.298	484.940	21.788	35,3	248.352

Table 34 – PV results

Renewable penetration is the fraction of renewable energy produced, divided by the total load. Figure 22 shows its average trend per month and yearly.

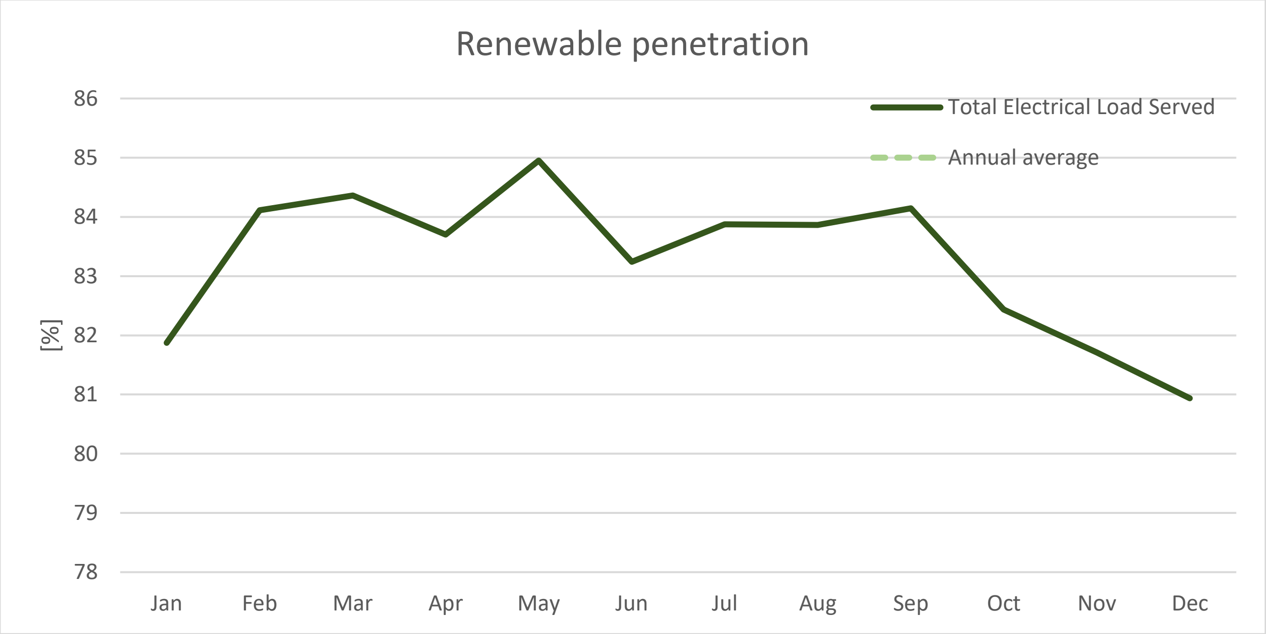

Figure 22 – PV renewable penetration

Figure 23 indicates how electric demand is satisfied during different months of the year: a fraction (varying approximately between 6 and 35%) is provided by owned photovoltaic system, while the remaining electricity needed is purchased from national grid.

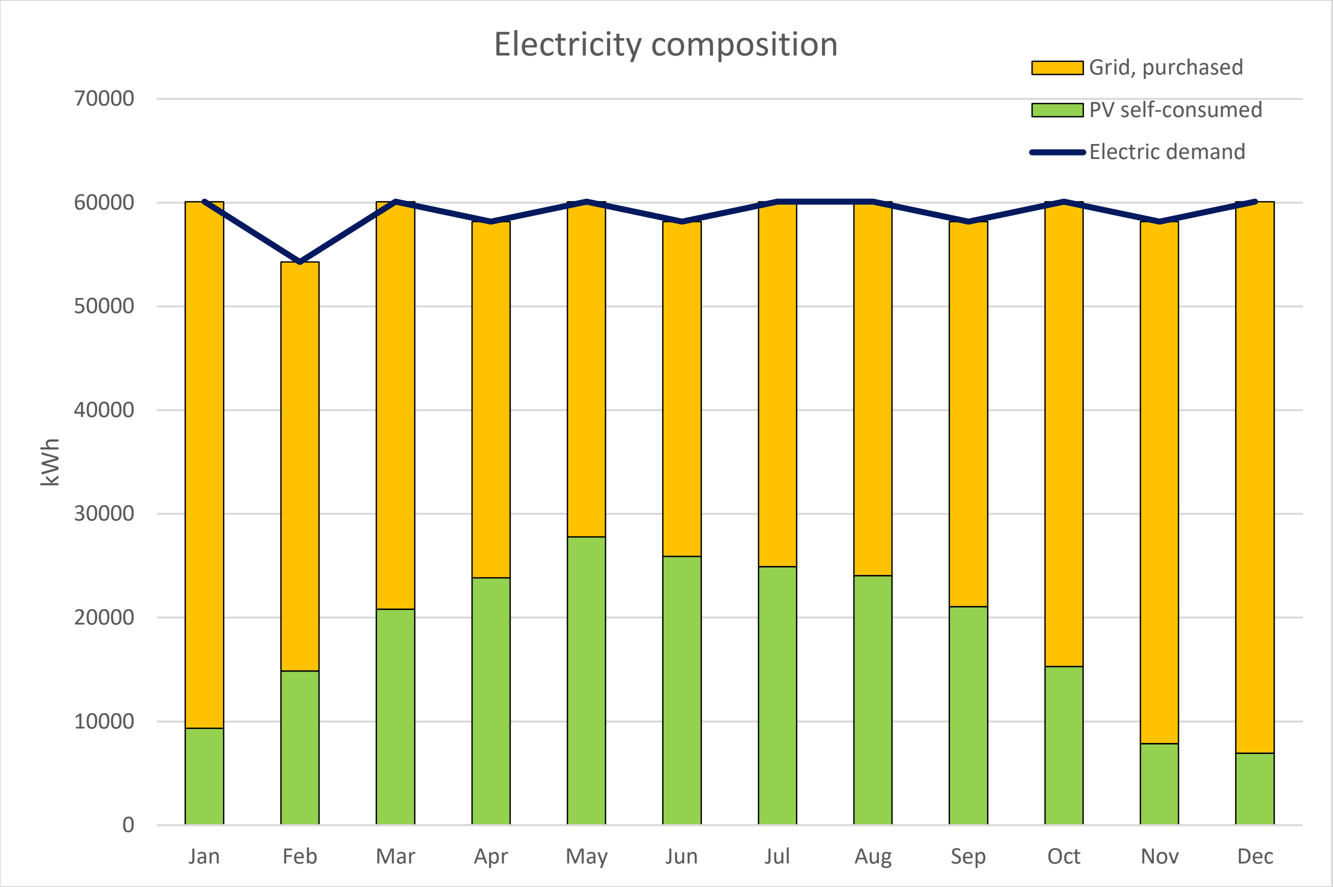

Figure 23 – PV yearly electricity composition

As it can be noted from Figure 23, due to geographical conditions of the area, December is the month with the lowest photovoltaic production, while May is the one where it is the highest. In particular, from simulation data, December 4th and May 5th are respectively the worst and best day of the year for solar irradiation: that's why they were chosen to illustrate, in Figure 24 and Figure 25, with hourly timesteps, electricity production and trading with the grid during a day.

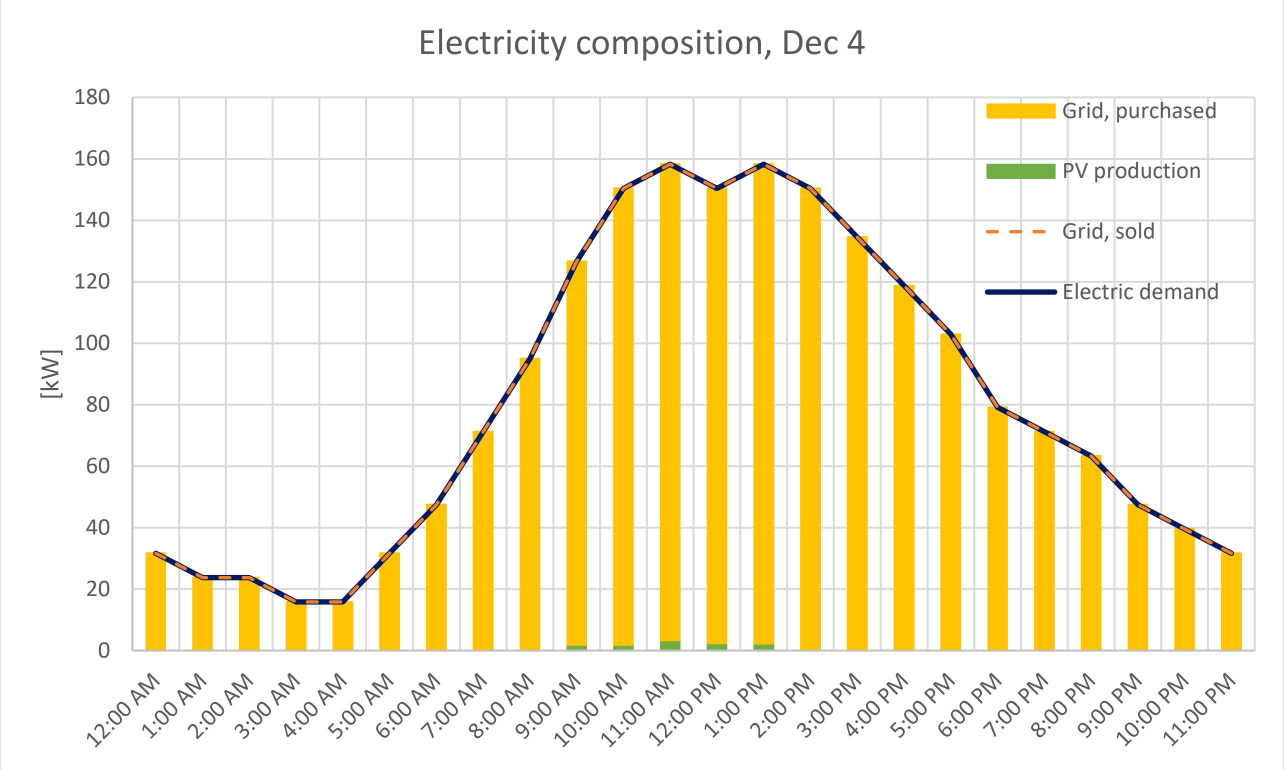

Figure 24 – PV daily electricity composition (worst)

In winter net photovoltaic energy production is very low and it is concentrated in the hours around midday. In the case of 4th December it barely appears in the total electricity consumed by the plant. Even more so there is no exceeding energy production, so the curve for electricity sold to the grid system is zero everywhere, laying just on the curve of electricity demand.

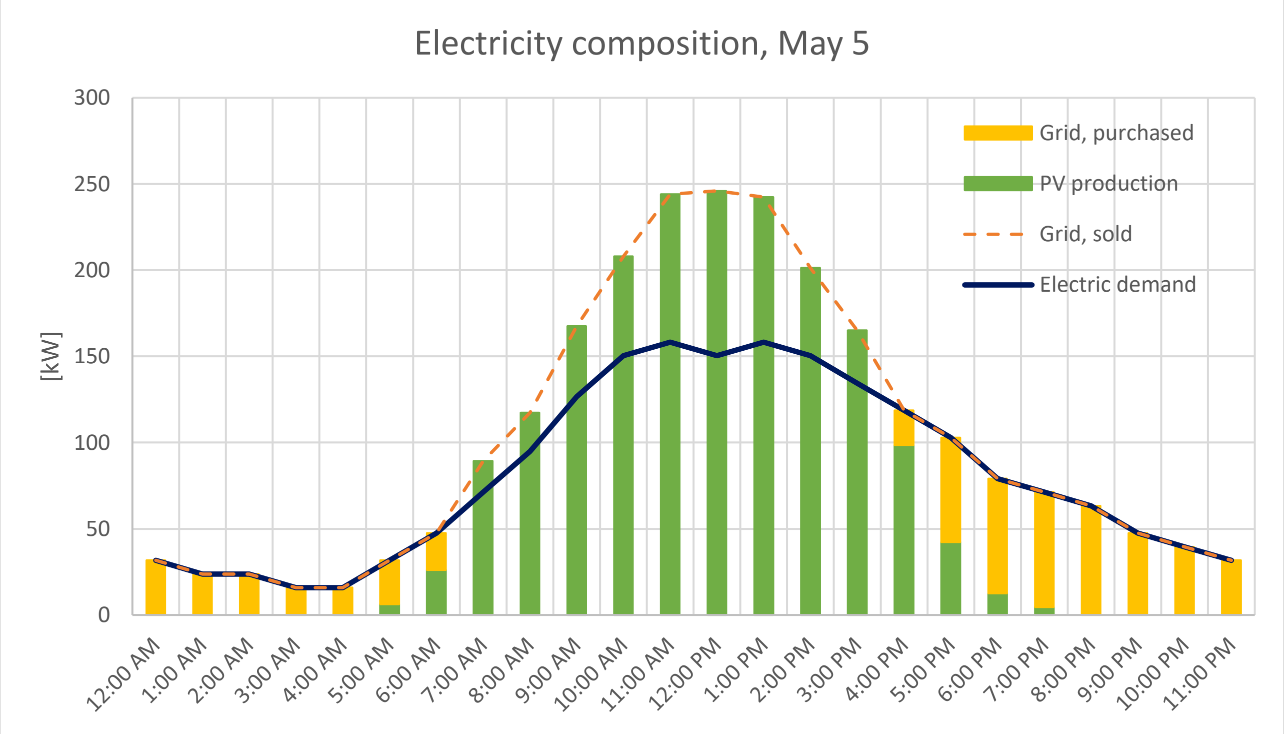

Figure 25 – PV daily electricity composition (best)

The 5th of May is the more favourable day for energy production from the sun, as there is a lot of daylight hours and electric demand of the distillery can be fully satisfied from 7 am to 3 pm. In this timeframe, renewable production is so high that it exceeds factory's demand: the surplus is represented in Figure 25 by the difference between with orange dashed line and the blue demand curve over which it lays and it indicates the amount of energy sold to the grid.

Configuration 3.1 – One battery

At least initially, only one unit battery was added to the model in order to explore how electricity production and consumption change, especially in summer months, when the electric storage system can delay the usage of energy produced by photovoltaic modules. Figure 26 shows how components and electricity streams change with the introduction of a battery storage (independently on how many units are there).

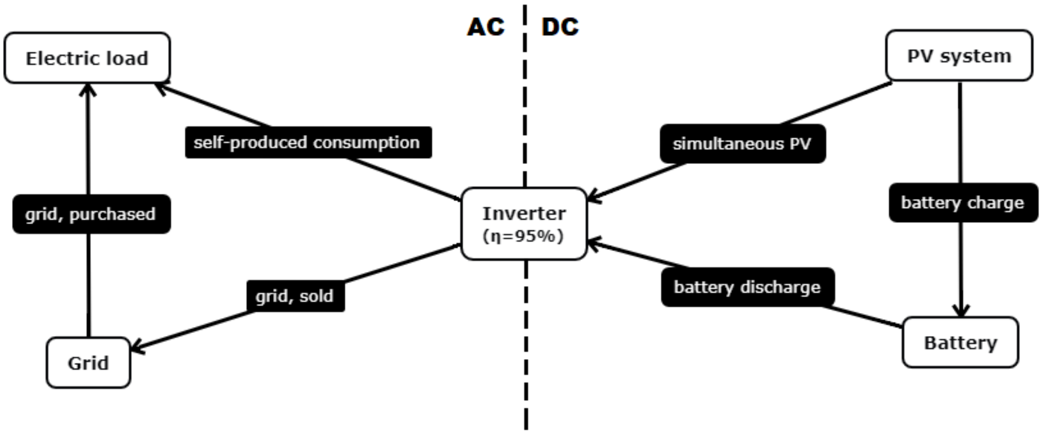

Figure 26 – battery configuration

Main results of the simulation with one battery are reported in Table 35:

PV capacity [kW]	Battery capacity [kWh]	PV production [kWh/y]	Grid purchases [kWh/y]	Grid sales [kWh/y]	Renewable penetration[16] [%]	CO_2 emissions [kg/y]
287,82	55,03	271.592	470.468	20.729	37,3	240.942

Table 35 – one battery results

Annual composition of electricity consumed is not so different from the case of photovoltaic only (see Figure 27).

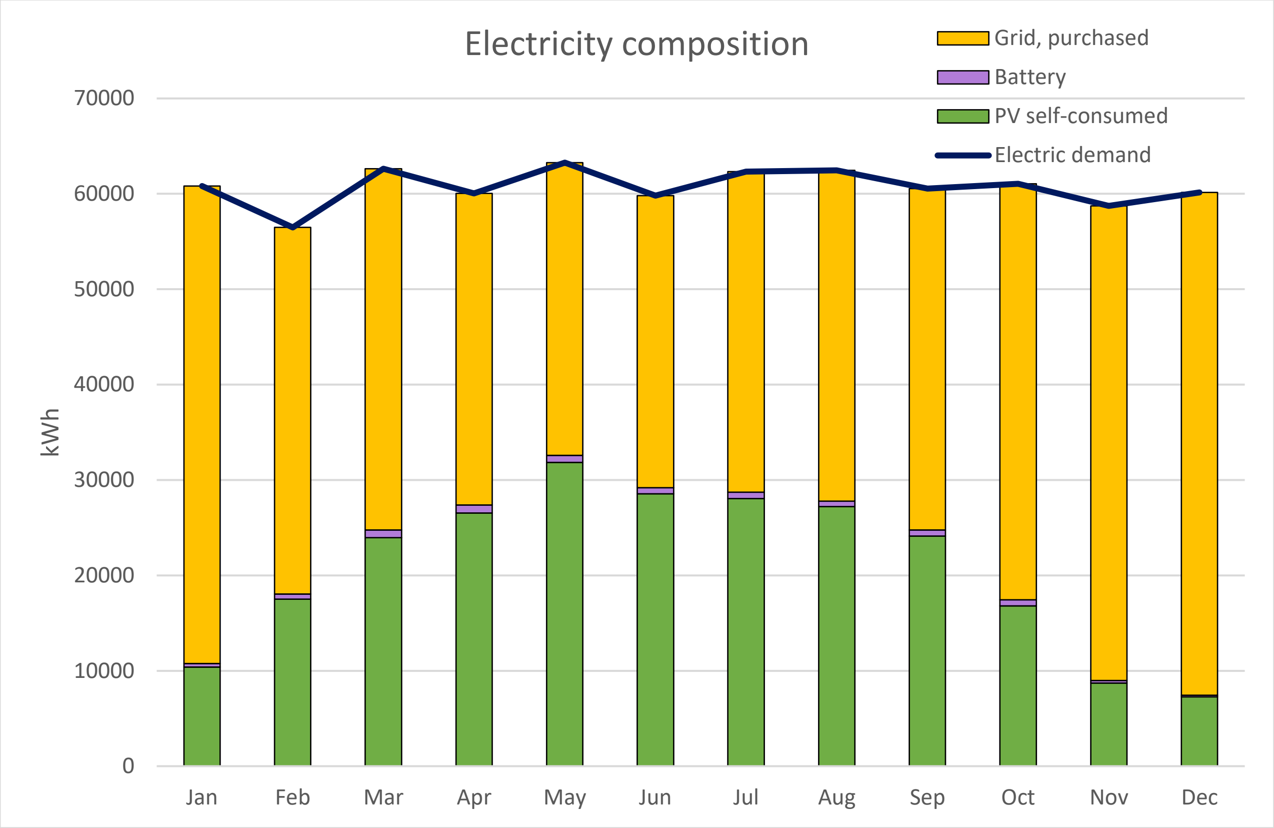

Figure 27 – one battery yearly electricity composition

Corresponding daily electricity trend on the best possible day is visible in Figure 28, while in December the situation remains unchanged.

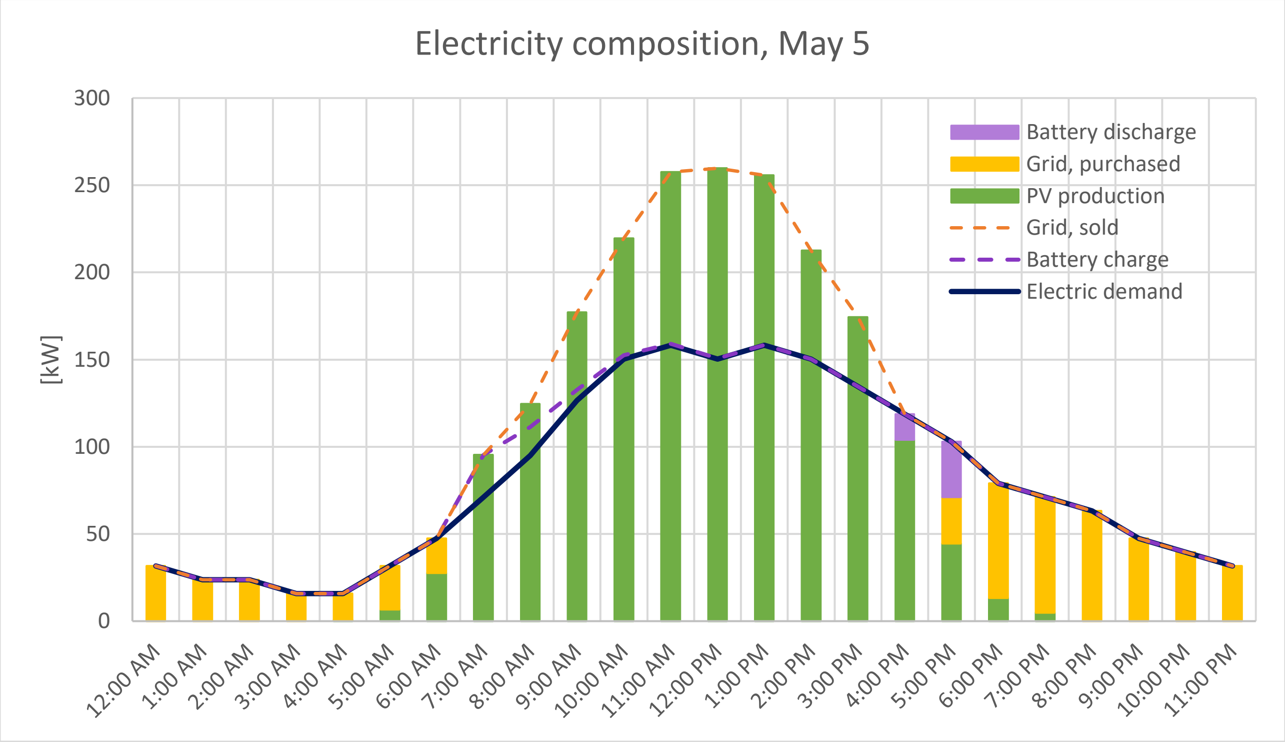

Figure 28 – one battery daily electricity composition (best)

Here violet curve and bar show how, when PV production exceeds electric load demand, it is employed to charge the battery and when PV production is not enough, energy stored in the battery is used to compensate the difference, before relying on purchasing from the grid.

Configuration 3.2 – ten batteries

Keeping in mind the daily chart of May 5th in configuration with PV system only (Figure 25), the difference between all energy produced during the sunlight hours and the one that is consumed, that is electricity sold to the grid, apart from electricity losses due to the efficiency of inverter, is reported in Table 36, together with PV production and electricity demand, with hourly timesteps.

Time	PV power output [kW]	Electric demand [kW]	Grid, sold [kW]
7:00 AM	93.92	71.21	18.01
8:00 AM	123.47	94.95	22.35
9:00 AM	176.29	126.6	40.88
10:00 AM	218.89	150.34	57.6
11:00 AM	256.82	158.25	85.73
12:00 PM	258.96	150.34	95.67
1:00 PM	255.09	158.25	84.09
2:00 PM	211.99	150.34	51.05
3:00 PM	173.85	134.51	30.64

Table 36 – highest daily surplus production

Summing up all the surplus energy, the total exceeding production on that day is 486,02 kWh. Thinking on how to exploit that energy later on directly in the distillery, the number of battery units was incremented up to 10, for a total nominal capacity of 550,34 kWh, in order to observe how storage increased of one order of magnitude would affect system production and self-consumption. An overview of system results is reported in Table 37:

PV capacity [kW]	Battery capacity [kWh]	PV production [kWh/y]	Grid purchases [kWh/y]	Grid sales [kWh/y]	Renewable penetration[16] [%]	CO_2 emissions [kg/y]
403,96	550,3	381.182	373.469	26.680	51,9	191.266

Table 37 – ten batteries results

In this case, the optimal solution found by the software comprehends a bigger photovoltaic plant. However, in December the chart remains the same, since the PV production is low due to scarce irradiance and not to the nominal capacity of the system. In May, instead, the change in daily production is really well visible.

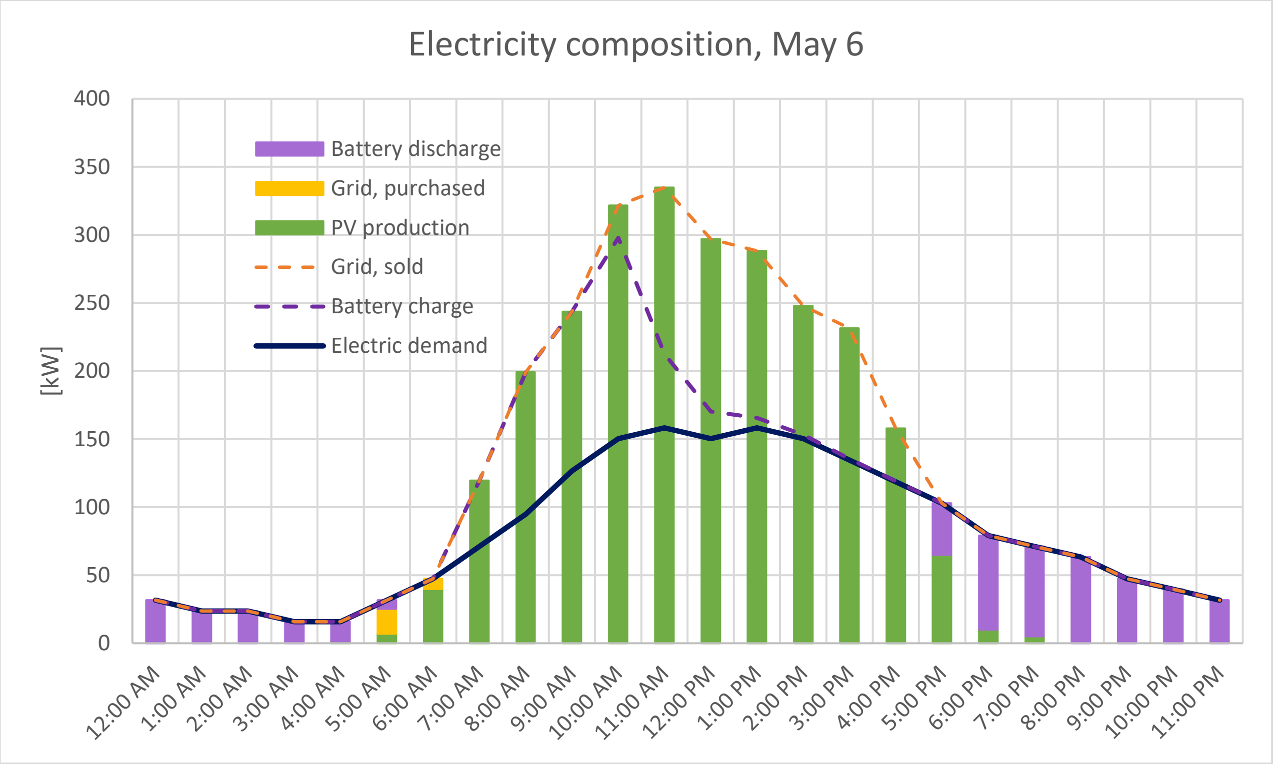

Figure 29 – ten batteries daily electricity composition (best)

Figure 29 shows how battery is fully charged in the morning with excess PV production. Since the best day for charging is May 5th, here the day after is plotted, when the energy stored in it can be used from 5:00 PM until 4:00 AM of the next day (the one in Figure 29), avoiding completely to purchase electricity from the grid during the night, until 5:00 AM, when a very little electric energy is bought for only 2 hours, when the sun starts charging batteries again.

For having an overall view, yearly composition of consumed electricity in the plant is reported in Figure 30, where the component coming from stored energy in the battery is neatly visible.

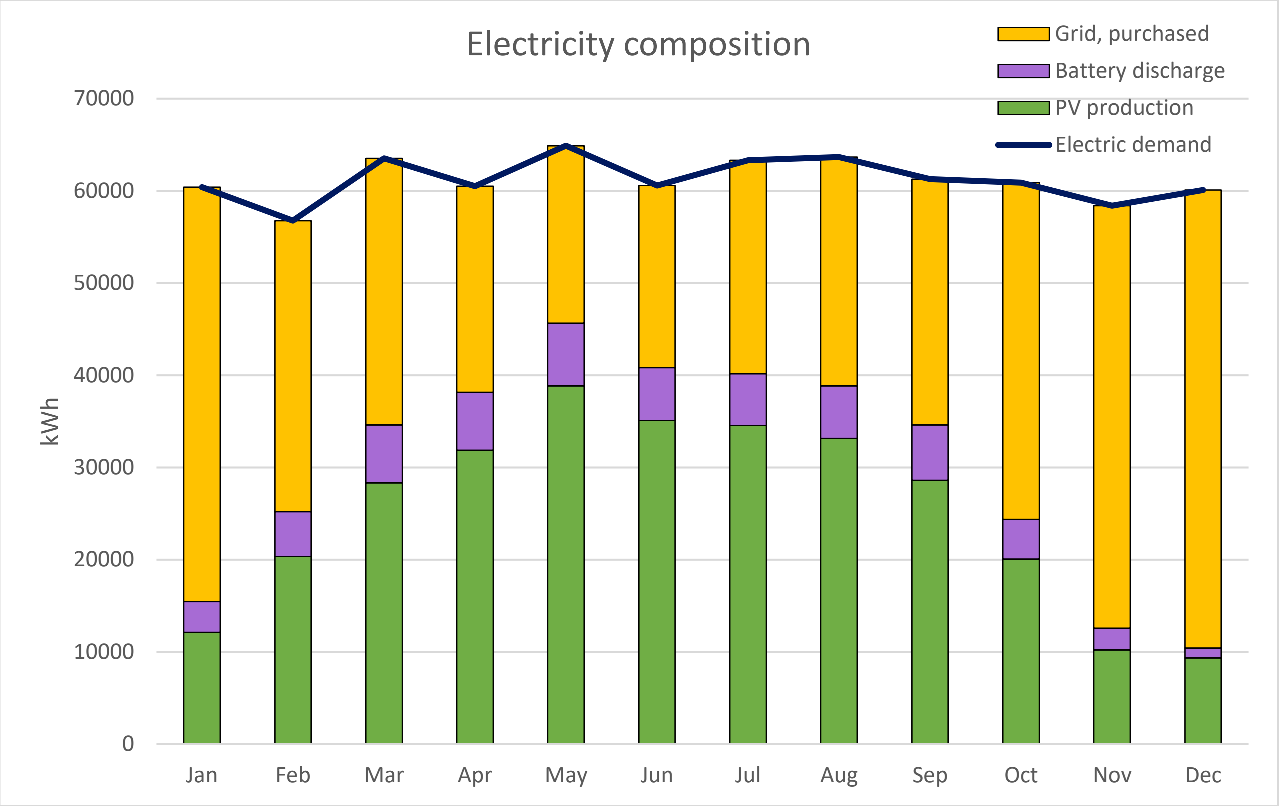

Figure 30 – ten batteries yearly electricity composition

Comparison

Table 38 – configurations comparison, containing main dimensioning data of the configurations, allows to compare energetic values of the different solutions. All data refer to one year of simulation.

Configuration	**Base case**	**PV only**	**One battery**	**Ten batteries**
PV capacity [kW]	0	272,67	287,82	403,96
PV production [kWh]	0	257.297,6	271.591,9	381.181,6
Batteries number	0	0	1	10
Battery capacity [kWh]	0	0	55,03	550,34
Grid purchases [kWh]	707.585,4	484.940,2	470.468,2	373.468,7
Grid sales [kWh]	0	21.787,6	20.729,3	26.679,5
Renewable penetration[16] [%]	0	35,3	37,3	51,9
CO_2 emissions [kg]	362.376	248.352	240.942	191.266

Table 38 – configurations comparison

A big difference lies in the production with photovoltaic modules, that is directly proportional to PV installed capacity and increases with increasing capacity of storage. The more substantial change is observable in electricity purchased from the grid, that is way less with the installation of a PV plant and further less with the introduction of a storage system. As a consequence of using more electricity obtained with the solar PV plant than electricity coming from the grid, the fraction of renewable sources over the total load increases from 0 to 51,9%. This value is definitely higher than the share of renewable generation of the national grid, that, as previously reported, in UK is around 37% [189]. Obviously, increased renewable penetration implies reduced emissions: the installation of solar PV plant lowers CO_2 emissions by more than 30%, arriving to almost cut in half emissions with the configuration with 10 batteries. Release of other pollutants such as sulphur dioxide and nitrogen oxides is very low with respect to carbon dioxide emissions. A graph comparing emissions of all configurations is shown in

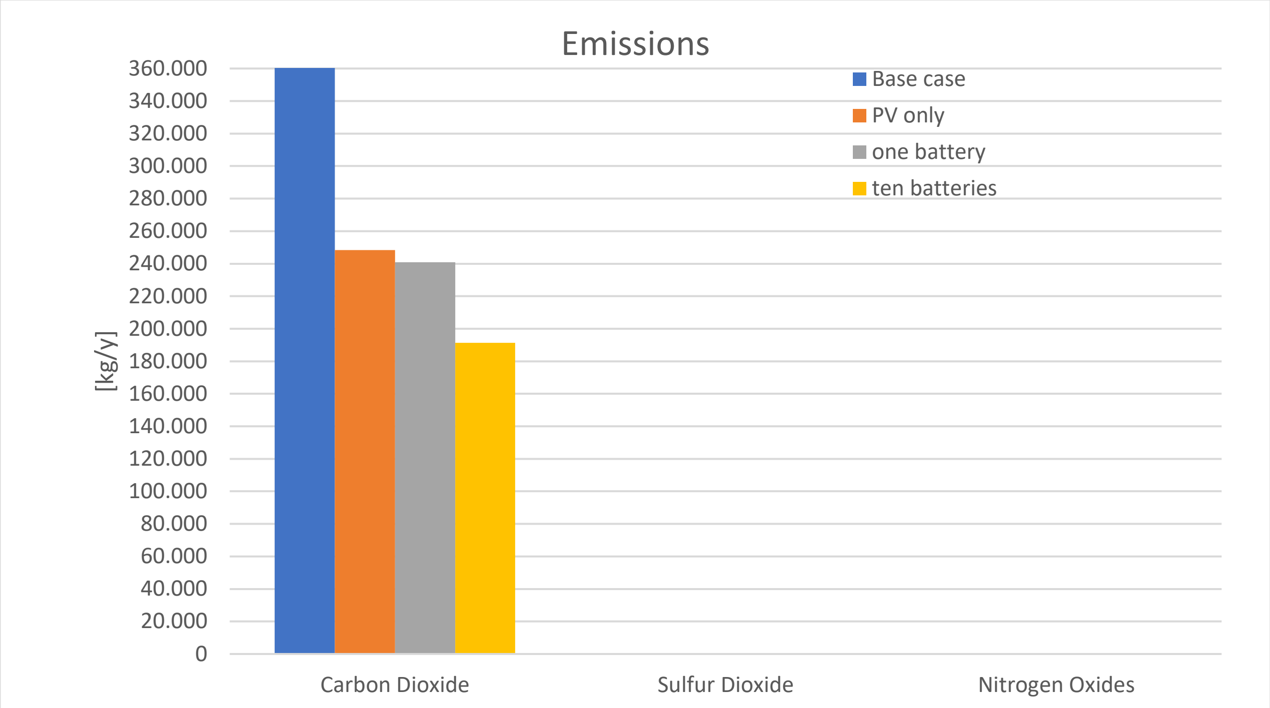

Figure 31 – emissions

Costs

Until this point, only energetic and environmental considerations were made upon electric design and dimensioning, but now it is time to look at the economical part of all the systems.

Configuration 1 – base case

Starting from the fact that the distillery is already connected to electric grid, there is no initial investment in the base case. The only expenses are operational costs, that are difference between electricity purchasing cost and sell-back price, amounting to 106.279 £ per year, for the whole plant lifetime, that is set to 25 years.

Configuration 2 – photovoltaic only

As it can be expected, photovoltaic plant requires a high initial investment, consisting of 316.299 £, but then operation and maintenance costs are low: only 2.181£ per year. On the other hand, electricity production from solar source allows to purchase less energy from the grid and sell some of it, lowering the total OPEX of the distillery energy system at 70% with respect to base case. Figure 32 and Figure 33 show respectively nominal and discounted cash flow of the configuration with solar photovoltaic, highlighting the difference between electricity trade costs with the base case (dashed line).

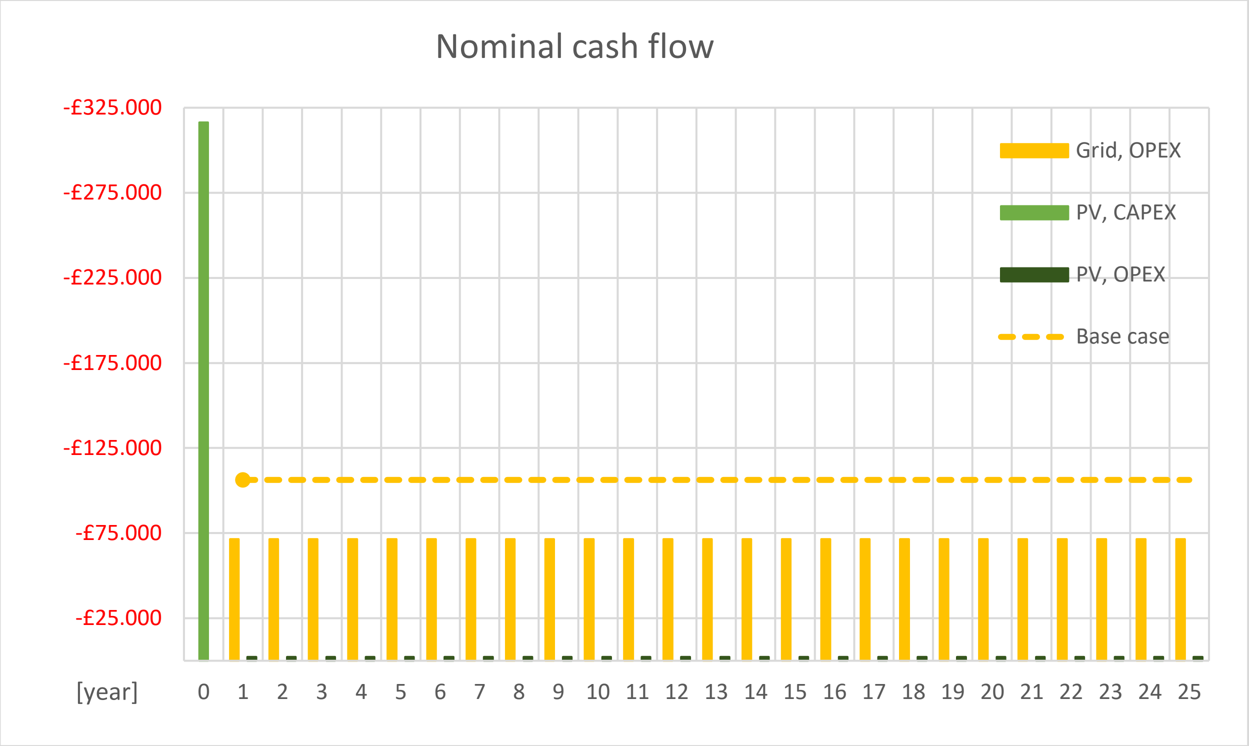

Figure 32 – PV nominal cash flow

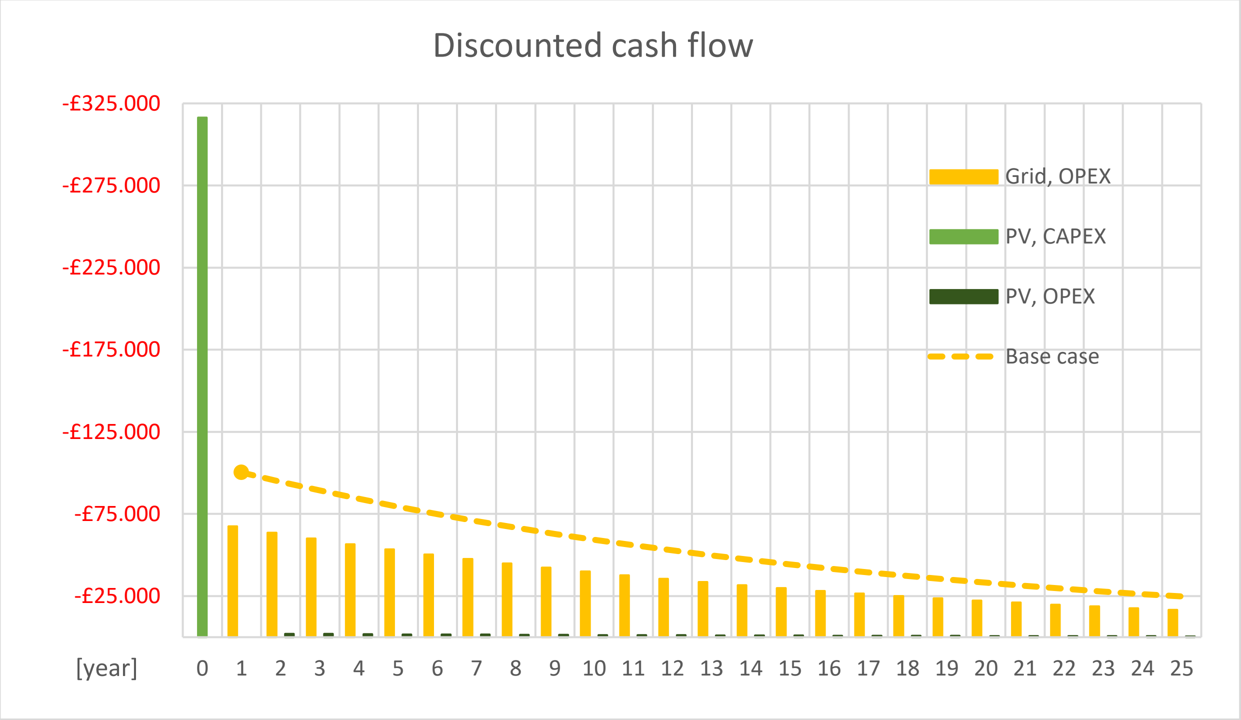

Figure 33 – PV discounted cash flow

Configuration 3.1 – one battery

Figure 34 shows calculated nominal cash flow for the configuration with a single Li-ion battery. Battery investment cost is visible in the chart, but still very little compared to capital cost of photovoltaic modules. Since batteries have an expected lifetime lower than overall plant, after some years they need to be replaced with new equipment: replacement costs can be noted on the 20th year in Figure 34. However, at the end of 25 years, battery is still working and this is taken in consideration with salvage value, that consists of 23.269 £ but is not reported in Figure 34. Operational cost of storage is lower than PV OPEX, that is already not so significative. Operational costs from the grid are just lower than the ones in configuration with PV only, as it can be seen in Figure 34 comparing the dashed grey line with yellow bars. Discounted cash flow is not reported, as it has a similar trend in all configurations.

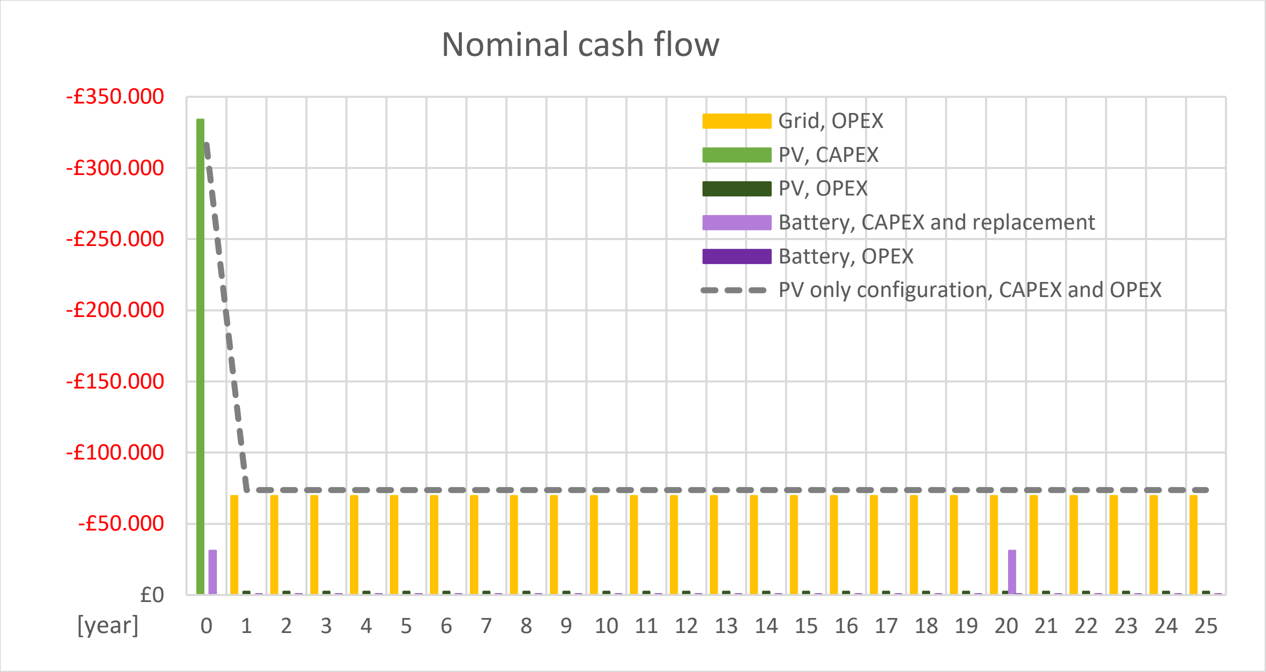

Figure 34 – one battery cash flow

Configuration 3.2 – ten batteries

Figure 35 contains the same kind of data, but for the configuration with a 10 times bigger storage.

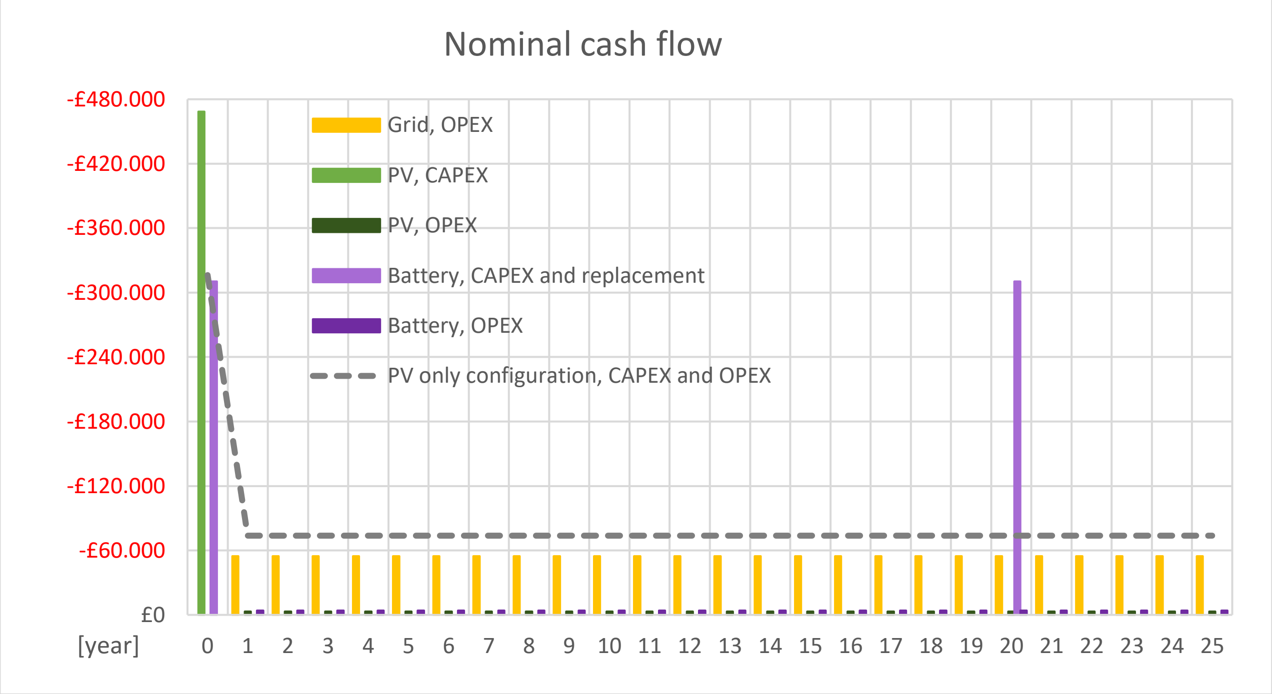

Figure 35 – ten batteries cash flow

In this case, storage system capital cost is very relevant, reaching more than 310.000 £. Also in this configuration, of course, batteries need tot be replaced after their expected lifetime has expired: this is the reason of the cost peak after 20 years. Salvage value of the batteries after 25 years is 232.689 £, although it is not reported in Figure 35. However, making a comparison with the configuration with solar PV plant only, also the difference in electricity purchased from the grid is noticeable, consisting in 19.171 £/y.

Comparison

Summing up all nominal costs in the different configurations, regardless of the year in which they are paid, total values in Table 39 result. CAPEX costs are accounted only once, while OPEX costs are multiplied by the number of years they are spent, that is 25. Salvage for batteries is removed from total costs.

Configuration	CAPEX, PV plant [£]	CAPEX, battery [£]	OPEX, grid [£/y]	OPEX, PV plant [£/y]	OPEX, battery [£/y]	Operational time [y]	Total [£]
Base case	0	0	106.279	0	0	25	2.656.975
PV only	316.299	0	71.543	2.181	0	25	2.159.399
One battery	333.872	31.025	69.430	2.303	413	25	2.176.303
Ten batteries	468.592	310.252	54.553	3.232	4125	25	2.404.157

Table 39 – costs comparison

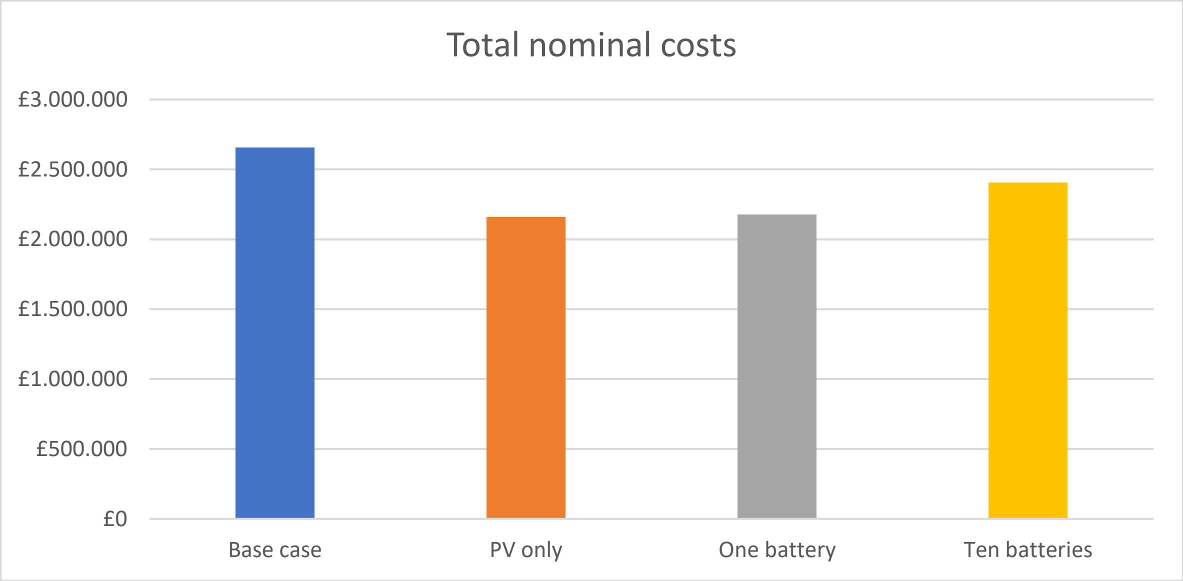

Figure 36 – total costs comparison

Total costs calculated in Table 39 are graphically showed in Figure 36 for a better visualisation.

Solar PV only configuration, even if it implies a high investment cost, it allows to save money during time, considering all the lifetime of the plant. Overall savings would be of 497.576 £ with respect to base case. The same reasoning is valid for all the other configurations, that after a period of 25 years result less expensive than the plant connected to grid only. However, money has not the same value in different times and also financial issues have to be taken in consideration. Table 40 reports economic data such as Net Present Cost and levelized Cost Of Electricity for all configurations, demonstrating that initial cost of battery storage is not justified by future returns of investment. A simple payback time has been calculated, as a ratio between capital costs and yearly savings due to less electricity purchased from the grid and some of it sold. Also looking at the payback time, the configuration with photovoltaic only seems to be the best choice.

Configuration	NPC [£]	COE [£]	Payback time [y]
Base case	1.358.606	0,1502	/
PV only	1.258.741	0,1350	9,7
One battery	1.291.407	0,1387	10,7
Ten batteries	1.612.778	0,1718	17,6

Table 40 – economic comparison

Thermal design

Grid

Natural gas is purchased from national grid at a price of 0,3004 £ per m^3, including the Climate Change Levy, from statistics by UK government in this case too, for medium industrial consumers that purchase in the range from 2.778 to 27.777 MWh per year of gas [187].

By-products production

As already seen, the two principal by-products resulting from the production process of Scotch whisky, and also the ones with the highest potential to be reused, are draff and pot ale. A detailed analysis on pot ale from a Scottish malt whisky distillery revealed that for each litre of alcohol produced, about 2,5 kg of draff, 8 l of pot ale and 10 l of spent lees are left. [49] Considering, instead, the yearly production of by-products based on whisky produced, real data from 8 distilleries for draff and from 4 distilleries for pot ale were put together in order to find a linear correlation between the three values [43].

$$\boldsymbol{Draff\ production\left[\frac{t}{y}\right] = whisky\ production\left[\frac{l}{y}\right] * 0,0025 + 125}$$

$$\boldsymbol{Pot\ ale\ production\left[\frac{l}{y}\right] = whisky\ production\left[\frac{l}{y}\right] * 7,857 - 1 * 10^6}$$

Figure 37 and Figure 38 represent respectively the production of draff and pot ale, indicating both real data and values calculated with the previous linear correlations. The red dots indicate by-products production of a distillery with a production capacity of 2 million litres of whisky per year, as in the case study.

Figure 37 – yearly draff production

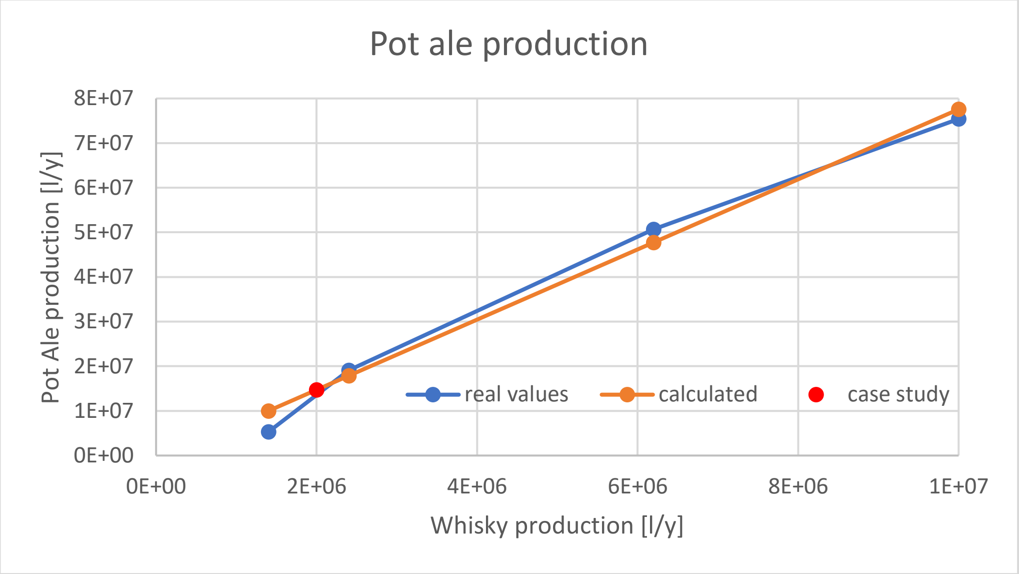

Figure 38 – yearly pot ale production

Calculated values result in an average production of 3,25 kg of draff and 7,48 litres of pot ale for every litre of whisky produced. In particular, for the case study of 2 million litres capacity, 2,56 kg of draff and 7,36 litres of pot ale are produced, that are values coinciding with the literature [17]. By-products production for the specific case study (red dots in the figures) are reported in Table 41, together with the values of draff and pot ale ratios with respect to the whisky production.

Production capacity [l/y]	**Draff production [t/y]**	**Pot ale production [l/y]**	**Draff/whisky ratio [kg/l]**	**Pot ale/whisky ratio [l/l]**
2.000.000	5.125	14.714.000	2,56	7,36

Table 41 – by-products production

Since pot ale is composed for 96% of water (the remaining 4% consists of solid matter) [48], its density is assumed to be equal to the one of water, that is 1000 kg/m^3, so that pot ale production in weight results to be 14.714 tonnes per year.

Energy production

Keeping in mind biogas yield values from Table 23 and by-products production from Table 41, the biogas that can be extracted from draff results in 3.218.500 m^3/y and the one produced from pot ale is 10.299.800 m^3/y, for a total biogas production of 13.518.300 m^3/y.

Biogas has a content of 55% methane and 45% carbon dioxide, in volume, as already established, and CH_4 has a lower heating value of 35,8 MJ/m^3, meaning that the biogas has a LHV of 19,69 MJ/m^3. Thus, all the biogas produced from draff and pot ale in a year has an ideal energy potential of 73.937.591 kWh.

Boiler

Biogas burners (usually dual-fuel) have normally efficiencies between 80 and 90%; for the case study the best possible option is considered, so that the biogas boiler has a 90% efficiency. If all the biogas produced through anaerobic digestion is burnt in this biogas boiler, 239.558 GJ/y of energy can be produced, corresponding to 66.543.832 kWh/y.

Whether the boiler is fed with biogas coming from anaerobic digestion plant or with natural gas purchased from the grid, it must in any case satisfy the thermal demand of the distillery in every moment, so its size has to be in line with the maximum peak of thermal power demand, that is 3616,5 kW.

The datasheet of a commercial dual-fuel steam boiler by Spanish ATTSU is taken as an example and reported in Table 42:

Company	Model	Usable thermal power [kW]	Steam production [kg/h]
ATTSU	HH 5.000	3.793	5.000

Table 42 – boiler properties

This could be used for providing heat power to the distillery, since its usable thermal power, indicated in the catalogue, is just above the thermal requirement of the plant.

Costs

A Master of Science group at the Strathclyde University in Glasgow developed an economic tool in order to assess the financial viability of different solutions about generating energy from co-products of whisky distilleries. [192] One option is generating power through a biogas boiler that provides steam demand needed in the production process. Biogas boiler capital cost information come from biogas boiler suppliers and they have been manipulated to obtain the following correlation in function of boiler capacity:

$$CAPEX = 13.97 * boiler\ capacity + \ 57484 \ \ [£]$$

Maintenance cost is supposed to be 5% of capital cost:

$$OPEX = 5\%\ CAPEX\ [£/year]$$

Following the previous correlations, the boiler of Table 42 would cost 110.472 £ as initial investment and 5.523 £ for yearly maintenance and operation (considering that in this case fuel would be for free). In Figure 39 both CAPEX and OPEX cost relation with boiler size are reported, and the values for chosen boiler are indicated as case study.

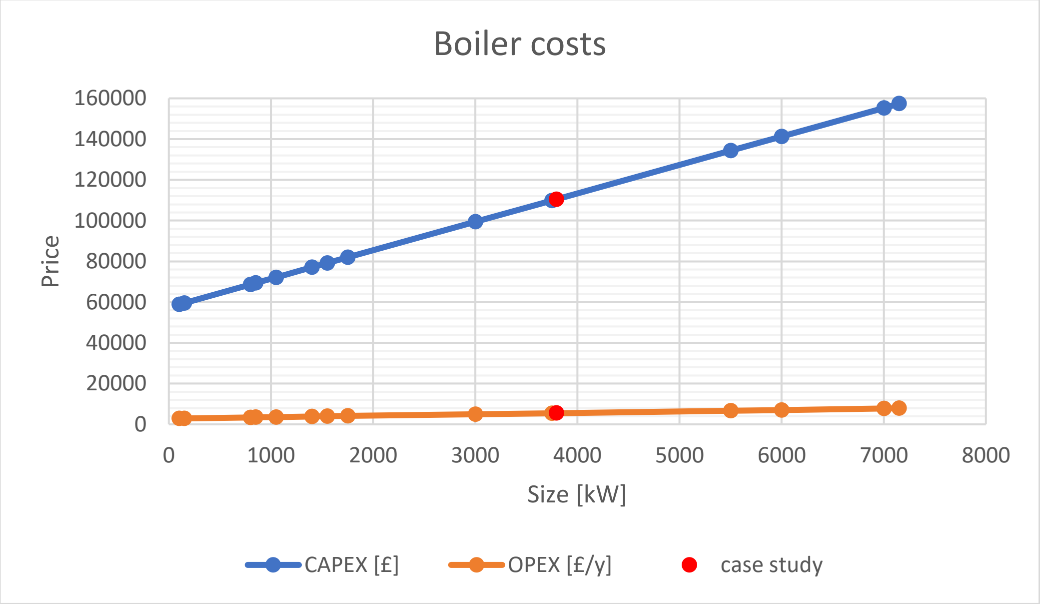

Figure 39 – boiler costs

CHP system

Since the energy potential of biogas extracted from by-products exceeds thermal demand requirement, as an alternative to biogas combustion in a burner, it can be employed in a combined heat and power system, for the simultaneous production of both electricity and thermal energy. A typical CHP system can have an overall efficiency of 75%, subdivided in 40% of thermal efficiency and 35% of electric one. With these data, 29.575.036 kWh of thermal energy and 25.878.157 kWh of electricity can be produced from the biogas extracted during one year. Comparing generation potential with electric and thermal demand, all energetic needs can be satisfied by a single CHP system fed by biogas produced with anaerobic digestion.

Costs

US EPA provided a catalogue of different CHP technologies [193], including their capital costs, that are influenced by the plant size. Figure 40 shows the dependence of total capital costs on plant electric capacity, expressed in £ per kW_e.

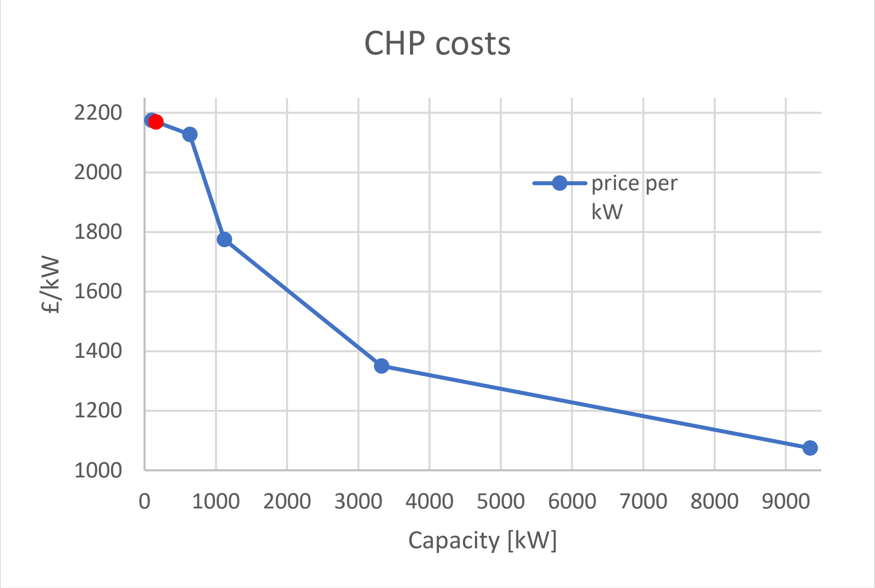

Figure 40 – CHP costs

Operation and maintenance costs are estimated to be 5 percent of capital investment.

$$OPEX = 5\%\ CAPEX\ [£/year]$$

CHP plant must at least satisfy electrical peak demand, so the entire system cost is estimated on the distillery's electrical needs and it is highlighted in Figure 40 with a red dot. CAPEX for case study would be 343.377 £ while OPEX results 17.169 £/y.

AD system costs

As an example, the feasibility study of a particular anaerobic digestion plant in France, is carried out. [194] It can process 100.000 tons of food waste every year and it is coupled with a CHP system. Annual gross heat and electricity productions are calculated to be respectively 43.662 MWh_{th}/y and 33.586 MWh_{el}/y. Involved waste is not explicated, it is a generic organic food waste with a biogas potential yield of 250 Nm^3/t treated in a dry anaerobic digestion process. For this reason, it is far from common range of AD plants associated with distilleries; however, it can be interesting looking at the single price of each item for the construction and operation of an entire AD + CHP plant:

CAPEX	**Average price [€]**	**Unit average price [€/MWh]**
Pre-treatment + AD plant	8000000	104
Dehydration + composting	3750000	49
CHP plant	1250000	16
Air and water treatment	2750000	36
Auxiliary systems (electrical and control equipment…)	2250000	29
Civil works	7500000	97
Contractors	3500000	45
Other (studies, start-up, fortuitous…)	3750000	49
Total	**32750000**	**424**

Table 43 – AD and CHP plant CAPEX

OPEX	**Price [€]**	**Unit average price [€/MWh]**
Staff	640000	8,29
Electrical energy	56250	0,73
Maintenance	651250	8,43
Water	8000	0,10
Oil	65000	0,84
Air treatment	75000	0,97
Water treatment	66000	0,85
Dehydration	32000	0,41
Landfill disposal	1120000	14,50
Hazardous water treatment	187500	2,43
Other (insurance, environmental plans…)	125000	1,62
Total	**3026000**	**39,17**

Table 44 – AD and CHP plant OPEX

In Table 43, an average value between lower and upper capital prices is calculated and it is related to total gross energy production, in order to have standardized data. Table 44 reports operational costs: same calculation to obtain normalized data is made.

To be more precise, a specific article investigates CAPEX and OPEX of different mesophilic anaerobic digestion plants, basing on technical data of 46 different AD projects, both with the aim of producing power and biomethane, of various sizes. They process several types of solid and liquid feedstocks, including food waste (both domestic and industrial), manures and energy crops. [195] Although the kind of feedstock processed deeply influences plant yield and characteristics, in this study their effect on costs is not considered, in order to have a more general view.
Capital cost of an anaerobic digestion plant comprises costs such as those of process equipment, civil engineering work (including plant construction, access road, etc…) and also costs regarding grid connection, professional fees, finance, eventual land purchase… A typical subdivision in CAPEX items [195] is reported in Table 45:

Capital cost item	**CAPEX share**
Pre-development	8 %
Construction	82 %
Grid connection	6 %
Other infrastructure	4 %

Table 45 – CAPEX subdivision

Among all data collected, a linear correlation can be found that approximates pretty well CAPEX trend in correlation with the plant design feedstock capacity. The range in question is from 14.000 to 280.000 tonnes of feedstock per year.

$$CAPEX = 151 * capacity_{feedstock} \left[\frac{t}{y}\right] + 3{,}1696 \quad [M£]$$

On the other side, operational costs of an anaerobic plant are either fixed or variable. Fixed component of costs include labour, machinery, purchased power, property costs, administration, while variable costs are those about maintenance, staffing, financial interests, feedstock supply and waste disposal. Same process is applied to OPEX costs, with the following result:

$$OPEX = 9918{,}7 * capacity_{feedstock} \left[\frac{t}{y}\right] + 988{,}29 \quad [k£]$$

As it can be seen later on, whisky by-products draff and pot ale, for example, have higher biogas yields with respect to common sludge feedstock: therefore, AD plants associated to distillery factories would have lower costs than farm plants.
More specifically, about distilleries industries that use anaerobic digestion for their by-products, financial information provided by the ADBA (Anaerobic Digestion and Biogas Association) were applied to 8 different real scotch whisky industries to investigate the costs of the potential AD plant associated with each of them. [52] The results indicate that a linear correlation can be found between costs and plant size (see "Real values" series in Figure 41 and Figure 42).

From numerical data provided by [52], the following equations of a straight line that generally follows the same trend are extracted:

$$CAPEX = 300.000 * size_{plant} \left[\frac{GWh}{y}\right] - 200.000 \; [£]$$

$$OPEX = 23.000 * size_{plant} \left[\frac{GWh}{y}\right] + 40.000 \quad [£]$$

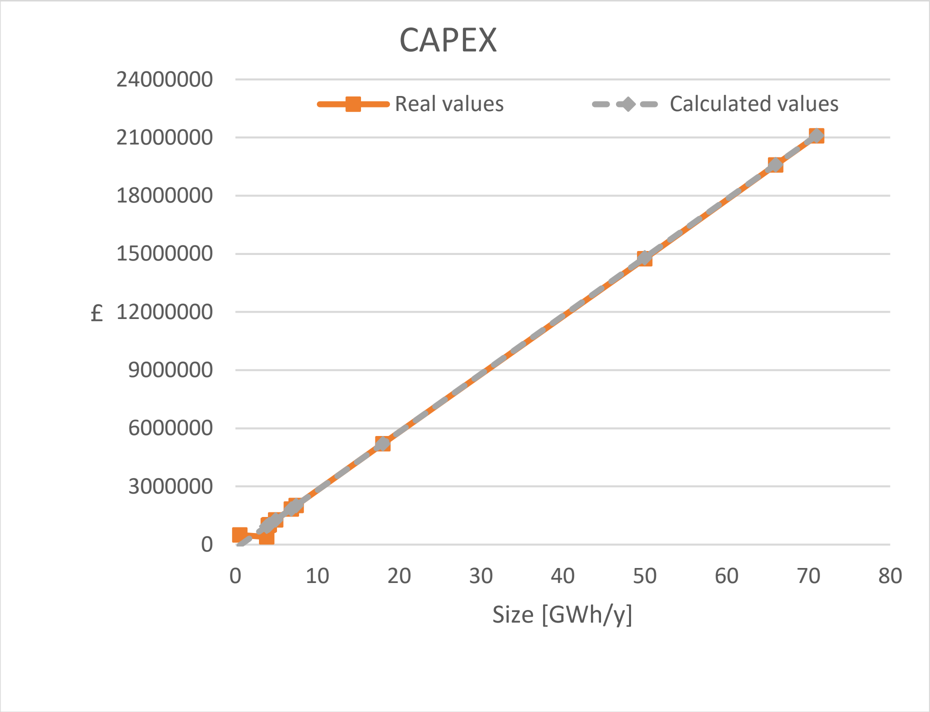

Figure 41 – anaerobic digestion plant CAPEX

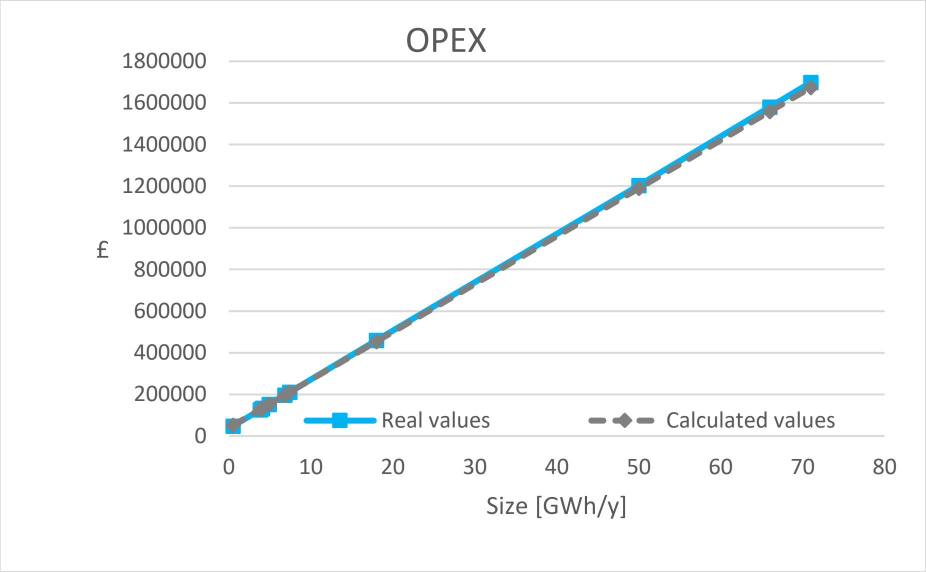

Figure 42 – anaerobic digestion plant OPEX

In Figure 41 and Figure 42 both series are plotted for both CAPEX and OPEX, to graphically see the trend of real plants values and the corresponding price, calculated with previous equations.
OPEX correlation is reliable, while CAPEX one is to be considered more of an indication. In general, accuracy is higher for plants bigger than 4 GWh/y.

Dealing with lower capacities, instead, two different studies for The Bioeconomy Consultants NNFCC (National Non-Food Crops Centre) [196], [197] agreed that the typical range of CAPEX for plants smaller than 300 kW_e is from 2.000 to 8.000 £/kWh_e, this including digester, feedstock storage, digestate storage, grid connection, boiler, groundwork, silage clamp, shredder, professional fees, CHP, cables & pipes, heat exchanger, pumps, mixer and loader. OPEX is made up of maintenance and repairs, that account for about 2% of CAPEX; together with operational costs such as insurance, that can be either included in the purchase agreement of equipment or affect for 1% of CAPEX; and also labour related costs, around 50 £/kW_e per year, that are difficult to predict, since they are not strictly related to plant capacity, but more to its technology complexity and automation level.

As a rule of thumb, one can estimate in a very simplistic way the costs of an AD plant in relation to the volume of digester tank, as follows [192]:

$$Capital\ cost = 2500 * digester\ volume\ [\text{£}]$$

$$Operating\ cost = 5\%\ capital\ cost\ [\text{£/year}]$$

Overview

A summary of main data from the dimensioning of the distillery energy plant are presented in Table 46, for a simple comparison.

	Power peak [kW]	**Demand [GJ/y]**	**Ideal energy production [GJ/y]**	**Energy produced by boiler [GJ/y]**	**Energy produced by CHP [GJ/y]**
Thermal	3616,5	58.165	266.175	239.558	106.470
Electric	158,25	2.545	/	/	93.161

Table 46 – energy production

Chapter 6 – Energy costs

Energy prices

Energy costs are rapidly increasing since the first months of 2021 all over the world [198].
Considering the size of the case study plant, Figure 43 shows the trend of energy prices in European Union from 2016 to 2021 based on data by Eurostat [199]. For electricity, costs for consumptions from 500 to 2.000 MWh are reported, while for gas the consuming range from 10.000 to 100.000 GJ is considered. The graph includes biannual data of electricity and gas prices for non-household consumers, including taxes, for 27 European countries (belonging to EU from 2020). All prices are expressed in € per MWh.

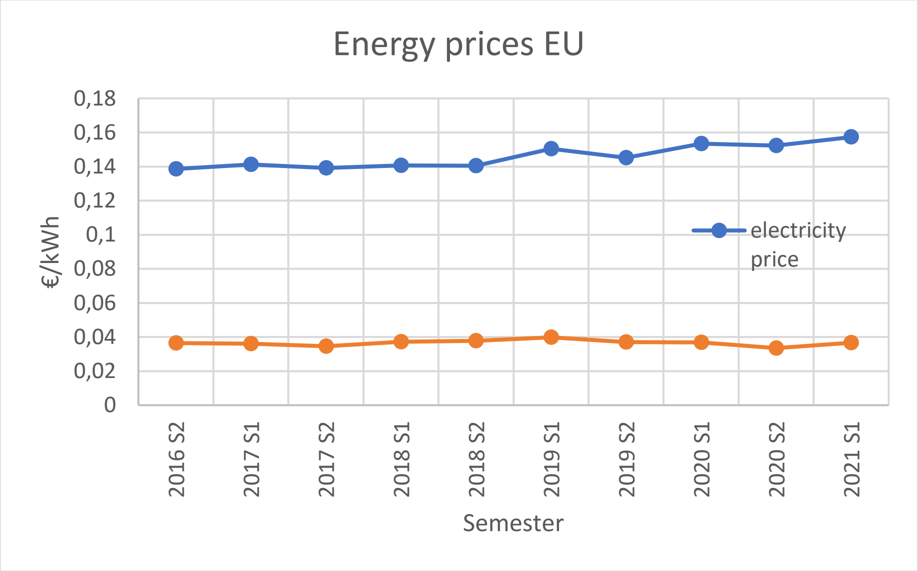

Figure 43 – EU energy prices

In 2021 the situation for electricity has become even worse, as it can be seen in Figure 44 from Eurostat [200], that gives a more complete view upon the evolution of energy prices in Europe from 2018 to January 2022.

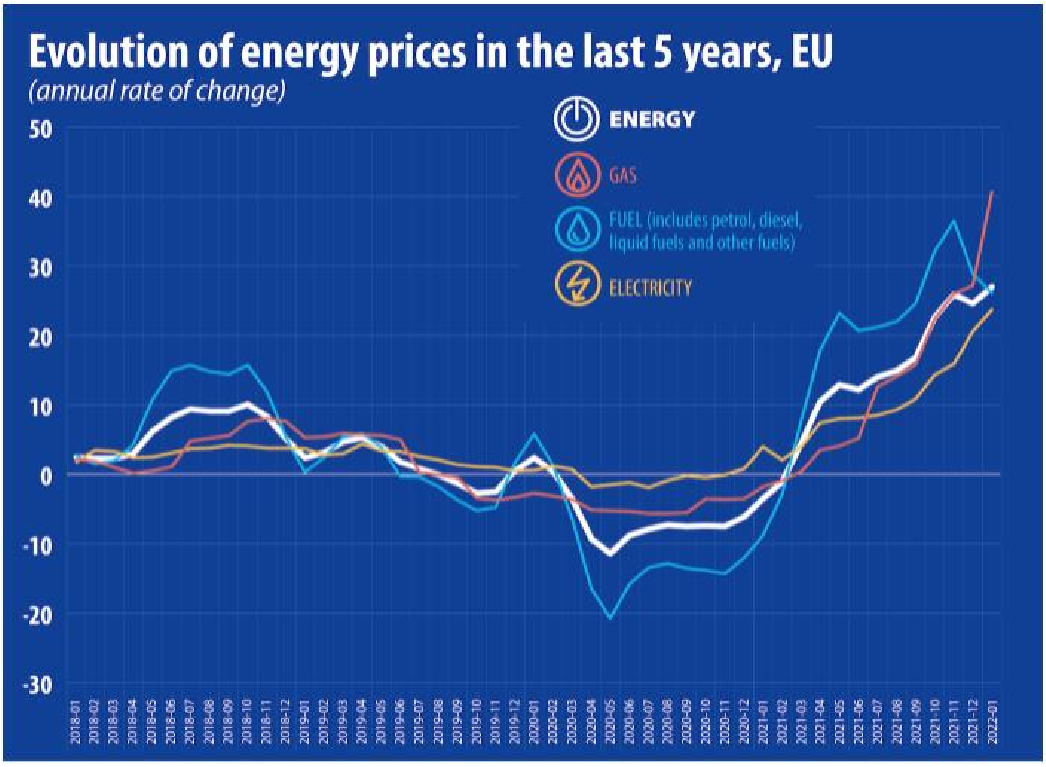

Figure 44 – EU energy prices evolution

Figure 45 from International Energy Agency statistics [198] reports the situation for some single countries, among which United Kingdom is the fourth nation with higher electricity costs, registering a remarkable slope since late 2020.

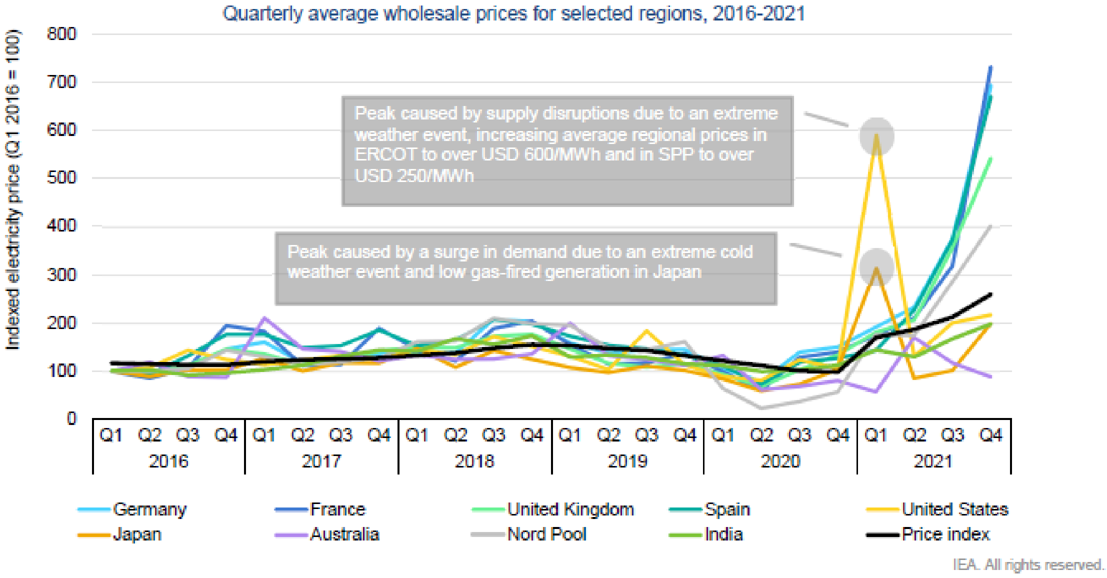

Figure 45 – global electricity sales

Last year UK's energy market is well visible in Figure 46 available on British gas website [201], where, apart from specific wholesale values that refer to domestic supply, further increases can be noticed towards the end of 2021 and starting 2022, reflecting economic trends of energy.

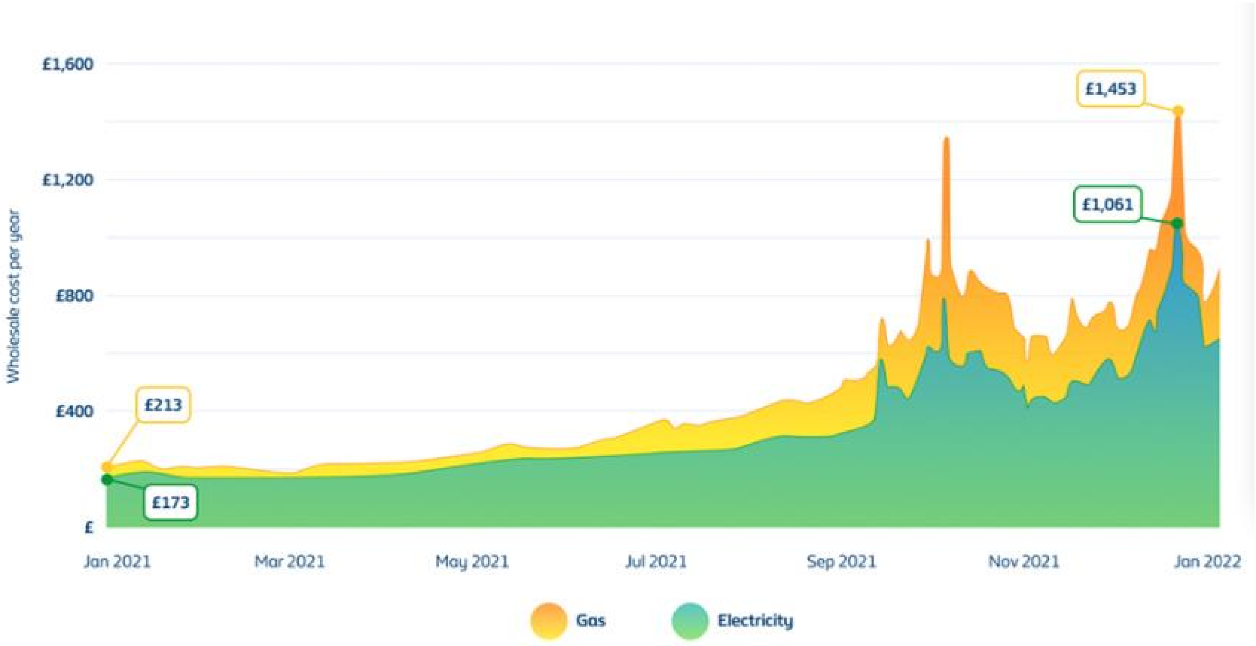

Figure 46 – UK 2021 energy prices

Incentives

Often, in order to help especially little companies and domestic users to improve themselves in a sustainable way, governments provide subsidies or incentives for renewable sources increase. Here below the situation in United Kingdom and in another European country, France, for comparison purposes are briefly described.

United Kingdom

In previous years UK government has granted some incentives for the production of both electrical and thermal energy, on 20 years payment basis. They were the Feed In Tariff (FIT), for power generation and selling to the grid, and the Renewable Heat Incentive (RHI), for the installation of new renewable heat technologies, both in Domestic and Non-Domestic field. Unfortunately, FIT stopped accepting new applications from 31 March 2019 and Non-Domestic RHI was officially closed to new applicants on March 2021 [202]. Since 1st January 2020 FIT was somehow substituted by the Smart Export Guarantee (SEG), that is a law that sets obligations for national energy suppliers that buy electricity from small-scale producers, if they comply with low-carbon criteria. It is available for those who installed in Great Britain solar PV, wind, hydro, anaerobic digestion up to 5 MW or micro-CHP up to 50 kW. Depending on which supplier is chosen, each contract has different duration and different price of purchase for energy exported to national grid, but it is guaranteed by the government that the price should be above zero (regardless of current wholesale electricity prices). [203] Waste and residue are considered suitable feedstock for anaerobic digestion to meet SEG criteria (for more information see [204]).

On the other hand, RHI subsidy for heat generation is intended to be replaced by the Clean Heat Grant, available since April 2022, that supports installation of small-scale heat pumps and biomass systems, to help domestic buildings' transition towards low-carbon heating systems [205]. Moreover, new environmental schemes have been released since November 2021: the Green Gas Support Scheme (GGSS), aiming to increase green gas share in the grid; and the Green Gas Levy (GGL) that imposes quarterly levy payments to licensed gas suppliers in order to fund GGSS. GGSS incentive is intended to support biomethane production through anaerobic digestion from waste or residue feedstock: at least 50% of biogas must be green in this sense [206]. It is available for a timeframe of 4 years and guarantees quarterly tariff payments for 15 years depending on the quantity of biomethane produced and injected in the grid [207].

France

In France production and use of biogas is largely supported, also by French government through issuing of dedicated laws and granting economic incentives, even if in the last multiannual energy programming (PPE) in 2020 biogas and biomethane assumed less importance, comparing to the past (lowering of grid injection purchasing fee and reduction from 10% to 7% of renewable gas share in national consumption composition are significative examples) [208]. Nevertheless, biogas facilities can benefit from a heat fund called *fonds chaleur*, created by French ministry of ecological transition in 2008 to incentive heat production with renewable energy sources, and in force until 2022. Its management on a regional scale is delegated to ADEME (*Agence de la transition écologique*) [209]. *Fonds chaleur* operate on three applications of biogas recovery installations: production of hot water or steam for industrial or collective (heating) use, recovering the entire energy potential of biogas; heat recovery from cogeneration production, again for industrial use or little district heating; biomethane injection (after biogas purification process) into the national gas grid. [210] Digestor installation expenses, instead, are not covered by heat funds [211]. Injection into transmission network is guaranteed by the obligation for distributors and suppliers to purchase biogas input for a period of 15 years, at a price fixed in advance that can vary depending on plant size (base price is comprised from 0.064 and 0.095 €/kWh) [212]. According to ADEME website, in 2021 the flat-rate subsidy per unit of annual production capacity is 0.04 €/kWh for injection, while the same subsidy for cogeneration amounts to 0.095 €/kWh [213].

Another possibility is to take advantage of support tools for renewable electricity production, through heat and power cogeneration. Electricity subsidies, called *guichets ouverts* (namely “open counters”), comprise purchase obligation for 20 years by suppliers at guaranteed tariffs for plants smaller than 500 kW, and bonus for remuneration on the market and technologically neutral tender for bigger facilities (> 500 kW) [209].

Conclusions

Since food and beverage is an important industrial sector with relevant consumptions and emissions, in this study it was investigated in order to explore decarbonisation possibilities and sustainable alternatives. After a brief introduction, the production processes of soft drinks, brandy and whisky were described, with further details about Scotch whisky production techniques and processes. Then, a long list of options about how to decarbonise a distillery producing Scotch whisky has been presented, analysing all different steps in its production chain. One among the most promising actions has been individuated as the exploitation of by-products resulting from industrial processes, through their anaerobic digestion in specific plants. The fuel resulting from anaerobic digestion is biogas, so its potential production from the three beverages mentioned in the first part has been analysed. Before introducing any practical example, a variety of system models were reviewed, with a particular focus on the ones that are useful for industrial sector simulations. Finally, a case study of a distillery in Scotland has been presented. Its electrical load and production were modelled through the means of one of cited models: Homer Pro. Here it was found that a renewable alternative as solar photovoltaic can be not only sustainable, but also economically convenient. For the thermal part of the plant, some calculations were made to investigate the thermal potential of by-products such as draff and pot ale and its comparison with the factory’s needs. It was demonstrated that by-products could feed the entire plant by themselves, representing a huge energetical treasure. In the end, an overall view was given about latest energy cost data and possible incentives in United Kingdom and Europe in general.

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