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Operating Energy Costs for Lighting and Aeration in Commercial Microalgae Cultivation (Spain, Scotland, France, Germany)

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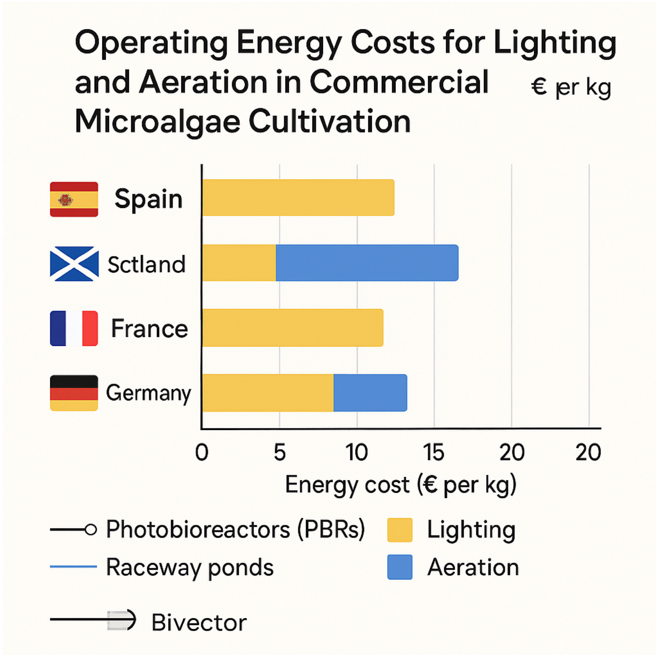
Commercial-scale microalgae farms consume significant electrical energy for **lighting** (if artificial illumination is used) and **aeration/mixing** (to circulate cultures and supply CO_2/oxygen exchange). Actual energy consumption and costs vary widely by system type and location. Below we present typical ranges and case studies for **photobioreactors (PBRs)** and **open raceway ponds (ORPs)** in Spain, Scotland, France, and Germany, highlighting the breakdown between lighting and aeration energy use where data are available. (All values refer to microalgae, not macroalgae, and are from post-2015 industry reports or studies.)



Spain 🇪🇸 – Sunlit Raceways and Photobioreactors

Spain offers abundant sunlight and a warm climate, enabling outdoor algae growth with minimal artificial lighting. As a result, energy use in Spanish systems is often relatively low, dominated by aeration/mixing (paddle wheels or pumps) rather than lighting. For **open raceway ponds** in southern Spain treating wastewater (e.g. the EU **All-Gas** project in Chiclana), total operational energy demand can be as low as ~0.5 kWh per cubic meter of culture . This equates to only a few kWh per kg of biomass in high-productivity ponds (on the order of 0.2–5 kWh per kg algae in large open systems) . At an electricity price of ~0.10 € per kWh, such energy use adds only ~0.02–0.5 € to the cost of each kilogram of biomass – a small fraction of total production cost. Indeed, techno-economic analyses indicate operational costs in open ponds can range ~0.5–2 € per kg algae , with low energy requirements in sunny climates keeping the energy cost component at the lower end of this range. The All-Gas raceway system even achieved **energy-positive** operation by converting biomass to biogas: it consumes ~0.5 kWh/m³ but generates ~2 kWh/m³ of bioenergy, demonstrating net energy gain and reduced overall costs .

For **photobioreactors in Spain**, the plentiful natural light means artificial lighting is usually unnecessary or limited to supplemental use. Energy consumption is therefore driven mainly by fluid circulation and aeration (CO_2 injection). A typical example is a tubular PBR in southern Spain, which requires about **1.5 kWh/m³** of culture for pumping/mixing . Given biomass concentrations of ~1–2 kg dry mass per m³ in PBRs, this corresponds to roughly

~0.75–1.5 kWh per kg biomass just for circulation. Real-world Spanish PBR facilities still face higher energy use per kg than open ponds (due to pumping through long tubes and friction losses). A recent Spanish case study found an **electrical consumption of ~50.8 kWh per kg** of dry biomass for year-round PBR cultivation of *Nannochloropsis* (single-species), and even higher (~131 kWh/kg) when alternating two species seasonally (to maintain productivity in cooler months) . These values are an order of magnitude greater than earlier optimistic projections (~5–6 kWh/kg) for ideal PBR operation , highlighting the challenge of scaling up even in sunny Spain. In terms of cost, with Spanish industrial electricity around €0.10–0.15/kWh, an energy use of 50 kWh/kg translates to about **5–7.5 € in electricity cost per kg** biomass. This aligns with estimates that energy can constitute ~14–17% of biomass production cost in closed PBR systems . Fortunately, optimizations can cut these costs: one study showed that in Spanish ponds/PBRs, reducing aeration and mixing at night (when photosynthesis stops) saved about **0.4 € per kg** biomass, reducing energy usage by up to 51% . In summary, Spain's commercial algae farms typically report **low lighting energy costs (due to natural sun)** and moderate aeration/mixing costs – e.g. on the order of **0.1–0.5 kWh/m³** for raceway mixing and ~1–2 kWh/m³ for PBR circulation, yielding total energy costs on the order of a few euro per kg of biomass.

Example: A 100 ha open facility in Spain was projected to produce biomass at **3.4 € per kg** (cultivation cost, excluding downstream processing), thanks to inexpensive land, free sunlight, and efficient paddlewheel mixing . With process improvements, this cost could drop to ~0.5 € per kg in the future . Energy-wise, such large raceway installations operate near the theoretical minimum energy input – one analysis suggests open pond cultivation needs only **0.2–0.5 kWh of electricity per kg** biomass under favorable conditions . At ~0.1 €/kWh, that is just €0.02–0.05 of electricity per kg biomass, reflecting how **Spain's climate minimizes lighting needs** and keeps aeration power low.

Scotland 🏴󠁧󠁢󠁳󠁣󠁴󠁿 – Challenges of Low Light, Innovative Solutions

In **Scotland**, the high latitude (55–58° N) and frequent cloud cover severely limit natural sunlight for algae growth. Commercial microalgae operations here generally cannot rely on open ponds (due to low year-round productivity) and instead use **indoor or closed photobioreactors** with **artificial lighting** to sustain growth. This dramatically increases energy consumption for lighting compared to sunnier regions. For example, the Scottish **ASLEE project** (Algal Solutions for Local Energy Economy) installed 16 × 1,000 L internally-lit PBRs in the West Highlands, using arrays of submerged LED light -L131】. These reactors are explicitly designed to absorb excess renewable electricity from local wind farms – highlighting how **lighting can dominate energy demand** in such climates. *"For phototrophic production of algae, you need a lot of light… that requires a lot of electricity,"* notes the project lead, underscoring that the PBRs can **"absorb quite a lot of the [electrical] l -L131】.

While specific Scottish energy consumption figures are not always published, lab-scale tests give an idea of magnitudes. In one trial, a 700 L photobioreactor with LED lighting powered intermittently by wind energy actually showed improved growth when light/dark cycles were used (mimicking natural day/ -L140】. However, the *power input* was substantial: a recent study in Central Europe (comparable in latitude to Scotland) reported that maintaining constant illumination in an LED-lit flat-panel PBR consumed the most energy of all processes, with specific power input on the order of **watts per liter** of c L1-L5 】. In that study, a fully-controlled flat-panel PBR (with continuous LED light and temperature control) had **~8.5× higher energy use per liter** of culture than a comparable system relying mainly on natural 5-L33】. This indicates that an algae reactor run with 24/7 artificial lighting in a dim environment could easily require tens of kWh per m³ per day – which translates to **hundreds of kWh per kg of biomass** produced if the growth rate is low. Indeed, without free sunlight, the **lighting energy** alone can dwarf aeration costs: for instance, one design study found that in a flat-panel PBR, keeping light intensity constant was the single largest energy sink, whereas in a tubular PBR the biggest draw was culture circulation (pu L1-L5】.

To mitigate costs, Scottish projects leverage *cheap or surplus power*. The ASLEE PBRs are run as a **"grid-balancing" load**, only drawing power when there is an oversupply of wind/renewable elect -L131】. Essentially, they accept intermittent lighting (algae tolerate some dark periods) to use otherwise-curtailed energy that has very low marginal cost. This approach aims to drive down the **effective electricity cost (€/kWh)** for lighting to make Scottish algae viable. Even so, the underlying consumption remains high. If we assume, for example, a PBR requires ~100 kWh of electricity to produce 1 kg of algae in Scottish conditions, at a standard rate of €0.15/kWh that's **€15 of electricity per kg** – clearly only sustainable if energy is obtained much cheaper (or if the algae product is high-value, such as nutraceuticals or salmon feed additives). In practice, Scottish photobioreactors can operate with *zero* lighting cost during periods of excess renewable generation (when electricity price drops near zero). Aeration and mixing energy in these systems are relatively minor by comparison, but still present – e.g. airlift pumps and gas injectors in the PBRs. Typical aeration/mixing requirements are on the order of **0.35–0.5 kWh/m³** for air-lift photobiore -L421】, similar to elsewhere. Thus, for Scotland, **lighting energy is the principal cost driver**, potentially accounting for well over half of total energy input, while aeration is a smaller (though necessary) contributor. Continued innovations (like only illuminating when power is cheapest, or using improved LED efficiency) aim to bring the **energy cost per kg** of Scottish algae down to competitive levels. For now, commercial operations are pilot-scale; they demonstrate that it is technically feasible to grow algae in Scotland year-round, but the *operating energy consumption for lighting is very high* without creative energy sourcing.

France 🇫🇷 – Moderate Climate, Mixed Systems

France lies between the climates of sunny Spain and cloudy Scotland, so French microalgae operations use a mix of strategies. Southern France has decent sunlight, whereas northern France has more temperate, variable weather. Commercial and pilot facilities in

France include both **open raceway ponds** (for example, some projects in coastal areas for wastewater treatment or biomass production) and **closed PBRs** (including innovative building-integrated PBRs and greenhouse-based systems). The energy consumption for **aeration/mixing** in French systems is comparable to general benchmarks: mechanical mixing with paddlewheels in raceway ponds typically requires about **0.1–0.3 kWh per cubic meter** of c -L421】. By contrast, closed photobioreactors using airlift or gas sparging need more energy to circulate the culture; a French study reports **~0.35–0.5 kWh/m³** for mixing in airlif -L421】. These figures assume no artificial lighting – i.e. outdoor or greenhouse operation with natural light.

In practice, many French microalgae initiatives try to minimize artificial lighting, given its cost. For example, the **AlgoSolis** technological platform in Nantes (47°N) tested vertical flat-panel PBRs on a south-facing building façade to capture sunlight. Even so, seasonal light variation means lower winter productivity. If supplemental lighting or heating is used to boost production, energy use rises. A **life-cycle assessment** based on an industrial-scale PBR plant (in a climate similar to France or northern Italy) illustrates the worst-case: it found overall electricity consumption around **267 kWh per kg** of biomass pr L1-L4】. The breakdown showed **pumping and aeration** accounted for ~43% (≈115 kWh/kg), **thermoregulation (heating/cooling)** ~40% (≈108 kWh/kg), and **LED lighting** ~15% (≈40 k 3-L17】. This case underscores how energy-hungry a closed system can become when operated in a non-optimal climate – the heating requirement was extremely high (likely a need to warm the culture in colder periods), and even a modest fraction of artificial lighting (15%) added significantly to the energy tally. The electricity cost for that scenario would be prohibitive for bulk products: **267 kWh/kg at €0.12/kWh is ~€32 per kg** in electricity alone. Commercial endeavors in France therefore focus on either **high-value products** (where such costs can be tolerated) or on improving efficiency.

On the positive side, French researchers are developing designs to use available solar energy more efficiently. One comparative study of PBR designs (flat-panel vs tubular) in a Central European context showed that an *indoors flat-panel PBR with constant LED lighting* had energy usage many times higher than sunlit designs, whereas a **helical tubular PBR in a greenhouse** achieved similar biomass outputs with a fraction of the energy. In fact, the **LED-lit flat panel required ~8.5× more energy per liter of culture** than the tubular reactor that relied on natural light (no active co 5-L33】. This finding aligns with the idea that **open or sunlit systems have much lower energy needs**. French efforts often integrate PBRs into greenhouses or even agrivoltaic setups to harness sunlight and reduce lighting power.

In summary, **typical energy consumption in France** might be intermediate: for an open pond in southern France, expect a few kWh per kg biomass (similar to Spain's low end), whereas for a closed PBR in northern France, it could be on the order of **dozens of kWh per kg** if operated year-round. Aeration/mixing is usually on the order of 0.1–0.5 kWh/m³ (lower end for ponds, upper end for -L421】. Electricity costs in France have historically been around €0.10–0.15/kWh for industry, so each 10 kWh of consumption adds about €1–1.5 to the cost per kg. The goal is to keep energy usage low enough that the **energy cost per kg** remains maybe €1–3. French pilot projects (e.g. **GREEN FEED** in Brittany for aquaculture feed, or wastewater algae treatments) report that energy optimization is key for economic viability. Wherever possible, **natural illumination and passive thermal regulation** are used to curb operating costs. Still, for high productivity or year-round operation, some **lighting and aeration cost** is unavoidable – these systems typically report total biomass production costs in the range of a few euros per kg, with energy being a significant slice of that (e.g. one source notes energy consumption can make up 14–17% of production cost in closed PBR s 9-L27】.

Germany 🇩🇪 – High-Value Production and Efficiency Focus

Germany has a climate somewhat similar to France's north (moderate temperate, ~48–54°N latitude) and some of the **highest electricity prices in Europe**, which historically incentivized German algae producers to maximize efficiency. German companies like **Algomed (Klötze)** and research institutions have long operated **large photobioreactor facilities** (typically tubular PBRs in greenhouses) to produce microalgae (e.g. *Chlorella* for nutraceuticals). These are commercial-scale and rely on natural sunlight through the greenhouse for primary illumination, with limited supplemental light. Aeration and circulation in such systems are significant energy draws: pumping dense algae broth through many kilometers of tubes and sparging CO_2 can consume on the order of 1–2 kWh per m^3 of culture (similar to the Spanish PBR figures). Over an entire growing season, this might average out to roughly **10–30 kWh per kg** of biomass in a German PBR, given somewhat lower annual insolation and slower winter growth. The **electricity cost impact in Germany** is greater – for example, at €0.20/kWh, a 20 kWh/kg energy use means €4 of electricity cost per kg. This is one reason German producers target high-value markets (where a few euros of energy cost is acceptable).

Encouragingly, recent technological advances in Germany (and neighboring countries) are pushing energy per biomass down. A Swiss-German startup **Arrhenius AG** demonstrated a novel PBR design largely powered by sunlight and efficient mixing: in pilot runs, they achieved an **energy consumption of only ~2.7 kWh per kg** of dry algae (extrapolated to continuous oper -L152】. This ultra-low figure – on par with the theoretical minimum – corresponds to an electricity cost of perhaps **€0.30–0.40 per kg** (assuming low-cost power), which is remarkably low. It was achieved by optimizing aeration, using pure CO_2, and relying on *natural light as the main energy s -L152】. The company claims production costs around $0.5 (≈€0.45) per kg biomass in such systems, feasible only because **lighting energy input is minimized** and efficient design cuts parasitic pow -L119】. This example shows the potential for **German/Swiss engineering to drastically reduce operating energy needs** for algae cultivation. On the other hand, if a German facility tried to use artificial lighting to boost winter production, the energy bills would soar. As noted earlier, fully artificially-lit PBRs can require tens of kWh per liter of c 5-L33】, which is economically untenable for bulk production. Thus, German operations typically confine cultivation to what sunlight (augmented by seasonally extended photoperiods in greenhouses) can support, and invest in **efficient aeration/mixing systems**. One analysis found that in PBR systems, **mixing (aeration pumping)** can account for >80% of the total energy consu 9-L27】 – so German engineers focus on low-friction loop designs, low-head pumps, and smart control (e.g. slowing circulation at night) to shave those costs.

In summary, **Germany's commercial microalgae energy profile** features *minimal artificial lighting* (due to cost), significant but optimized aeration/mixing energy, and a push toward real-world energy consumption of perhaps **5–20 kWh per kg** in modern sunlight-driven PBR facilities. Older or less-optimized systems might use more (50+ kWh/kg), especially if heating is needed in winter. With electricity ~0.18–0.25 €/kWh in Germany (pre-2022), even 20 kWh adds ~€4–5 per kg – manageable for high-value algae. For perspective, a study noted that at certain optimal flow rates a tubular PBR's net energy balance becomes positive (more energy in biomass than consumed) and the biomass production cost can be ~€3.2/kg dry 9-L57】. This suggests that at careful operating points, German systems can reach energy self-sufficiency. Indeed, if waste heat or cheap energy is available (some German farms are co-located with biogas plants or industrial CO_2 sources), the effective energy costs can be further reduced.

Summary of Energy Consumption and Costs by System and Country

- **Open Raceway Ponds (ORP)** – *Spain:* Very low energy input, ~0.1–0.3 kWh/m³ for paddlewheel -L421】, translating to ~0.2–5 kWh/kg biomass in large L1-L4】. Electricity cost: only ~€0.02–0.5 per kg (at €0.1/kWh). *France:* Similar range in sunny south; less common in north. *Scotland/Germany:* Rarely used due to climate; would have low energy per volume but extremely low productivity in these climates (not commercially favored). Open systems use **no artificial light**, so lighting cost = €0; aeration (mixing) is the primary energy expense.
- **Closed Photobioreactors (PBR)** – *Spain:* Outdoor PBRs use sunlight, with ~1–1.5 kWh/m³ for circu L1-L4】. That's on the order of 5–20 kWh/kg produced (lower end if productivity is high). Electricity cost maybe €0.5–2/kg. *France:* PBR energy use varies with design and latitude. Aeration/mixing ~0.35 -L421】; if no supplemental light, perhaps 10–30 kWh/kg. Any needed heating or occasional lighting will add to this (e.g. an industrial PBR in a temperate climate showed ~108 kWh/kg for heating and 40 kWh/kg for LEDs in one ana 3-L17】. Thus total can range from moderate (~tens of kWh/kg) to very high (hundreds kWh/kg) if run year-round with full controls. *Germany:* PBRs in greenhouses, focusing on natural light. Likely 10–20 kWh/kg in practice for well-tuned systems, but could be >50 kWh/kg in winter operations. *Scotland:* PBRs with **full artificial lighting**; energy usage per kg is extremely high (potentially 100–300+ kWh/kg in continuous mode). Only viable with virtually free electricity. Scottish pilots mitigate this by intermittent

operation using surplus wind -L124】. In PBRs, **lighting vs aeration** share of energy depends on usage: in Spain/Germany (sunlit), **aeration/mixing is ~80–90%** of energ 9-L27】, with lighting negligible; in Scotland or intensive indoor systems, **lighting can be >50%** of energy load (even >80% if fully lit L1-L5】.

To put these numbers in perspective, a **well-optimized sunlit system** (e.g. large raceway in Spain or advanced PBR in Germany) might consume **<5 kWh of electricity per kg** biomass – costing on the order of €0.5/kg – whereas a **high-intensity artificially-lit system** (e.g. indoor PBR in winter) could consume **>200 kWh/kg**, costing €20–30+ per kg in electricity, which is only justifiable for specialty products. Most commercial operations in Europe target the lower end by exploiting natural conditions and engineering efficiencies. As one cutting-edge example, Arrhenius AG's pilot PBR (central Europe) achieved ~2.7 -L152】, showing that **<3 kWh/kg (≈€0.3/kg)** is possible when **sunlight is the main energy source and aeration is optimized**. On the other hand, in the worst-case noted in literature, an older design photobioreactor used ~267 kWh/kg in a temperate c L1-L9】, illustrating the gap between early-stage systems and optimized modern designs.

In conclusion, **Spain** enjoys the lowest operating energy costs for algae (thanks to free sunlight and warm weather – lighting costs nil, aeration costs low). **Scotland** faces the highest lighting energy burden, but innovative use of cheap renewables can offset the €/kg cost impact. **France and Germany** fall in between: they use engineering solutions to minimize artificial lighting and improve aeration efficiency. Across all countries, there is a clear trend: *whenever sunlight can be relied upon, it is used to avoid electrical lighting costs; and wherever mixing or aeration is needed, engineers strive to reduce power per volume.* Real-world commercial data indicate **lighting and aeration energy consumption ranges** roughly as follows:

- **Lighting:** 0 kWh/m³ (for open ponds or sunlit PBRs) up to ~**0.5–0.8 kWh/L** (≈500–800 kWh/m³) in intensive LED-lit re 5-L33】. Most outdoor systems in ES/FR/DE use <5% of that upper range. Lighting cost ranges from €0 (sunlight) to potentially ~€15–20/kg (fully indoor at €0.15/kWh).
- **Aeration/Mixing:** ~**0.1–0.5 kWh/m³** of culture for commercial d -L421】. In large ponds, this is on the low end; in airlift PBRs, on the high end. Per kg biomass, this might be ~1–10 kWh/kg in productive systems (higher if productivity is low). Cost contribution is typically €0.1–€1.5 per kg from aeration.

Notably, one study points out that in closed PBRs, **energy for mixing can exceed 80% of total energy 9-L27】 when no artificial lighting is needed. Conversely, in a dim environment requiring full lighting, mixing might be <20% of the total (with light taking the lion's share). Operators thus adjust aeration rates (e.g. turning down at night) to save 5-L60】, and in climates like Spain's they avoid artificial lights altogether. As technologies improve (more efficient LEDs, better reactor hydrodynamics, etc.), the **typical energy consumption** is trending downward, narrowing the gap between sunny and cloudy locales.

References:

- All-Gas wastewater algae project (Spain) – energy balance: 0.5 kWh/m³ consumption vs 2 kWh/m³ energy -L206】.
- Open-pond operational ranges (post-2015 review): 0.2–5 kWh/kg and 0.5–2 €/kg for large-scale algae culti L1-L4】.
- Ruiz *et al.* (2016) Techno-economic projection – Spain 100 ha plant at ~3.4 €/kg biomass now, possibly 0.5 €/kg 7-L45】. Energy ~15% of cost, mostly 9-L27】; cutting nighttime aeration saves 0.4 €/kg (51% e 5-L60】.
- Pruvost *et al.* (2016, France) – mixing energy in raceway vs PBR: ~0.1–0.3 kWh/m³ (paddle wheel) vs 0.35–0.5 kWh/m³ (ai -L421】.
- Sukačová *et al.* (2021) – indoor vs outdoor PBR comparison: lighting is main energy load in flat-panel (Central Europe), with LED-lit PBR consuming ~8.5× more energy per L than sunlit d 5-L33】.
- LCA of industrial PBR (Europe) – **267 kWh/kg** total: pumping/aeration ~115, heating ~108, lighting ~40 3-L17】. Emphasizes high energy in moderate climates.
- Arrhenius AG pilot (2023, CH/DE) – achieved **~2.7 kWh/kg** using mostly natural light and efficient -L152】, confirming low energy cost (~€0.3/kg) when technical energy inputs are minimized.