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Climate Neutrality Concepts for the German Chemical–Pharmaceutical Industry

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Abstract: This paper intends to propose options for climate neutrality concepts by taking non-German international experiences and decisions made into account. Asia-Pacific and Arabic countries do have already same lessons learned by large-scale projects with regard to economic evaluations. Quite a few conceptual studies to generate the climate neutrality of the chemical–pharmaceutical industry in Germany have been published recently. Most of the studies differ even in magnitude but do not refer to or evaluate the other ones. These are all first theoretical feasibility studies. Experimental piloting is not far developed; only few and only stand-alone parts are operated, with no overall concepts. Economic evaluation is missing nearly completely. Economic analysis shows a factor 3 more expensive green technologies. Even if a large optimization potential of about 30% during manufacturing optimization is assumed as significant, cost increases would result. To make green products nevertheless competitive, the approach is to increase the carbon-source cost analogue, e.g., by CO_2/ton taxes by around EUR 100, which would lead to about factor 3 higher consumer prices regarding the material amount. Furthermore, some countries would not participate in such increases and would have benefits on the world market. Whether any customs-duties policy could balance that is generally under question. Such increasing costs are not imaginable for any social-political system. Therefore, the only chance to realize consequent climate neutrality is to speed up research on more efficient and economic technologies, including, e.g., reaction intensification technologies such as plasma ionization, catalyst optimization, section coupling to cement, steel and waste combustion branches as well as pinch technology integration and appropriate scheduling. In addition, digital twins and process analytical technologies for consequent process automation would help to decrease costs. All those technologies seem to lead to even less personnel, but who need to be highly educated to deal with complex integrated systems. Research and education/training has to be designed for those scenarios. Germany as a resource-poor country could benefit from its human resources. Germany is and will be an energy importing country.

Keywords: climate neutrality; green technology; power-to-X; sustainability; global warming potential; cost of goods; digitalization; process intensification; circular economy; section coupling

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1. Introduction

The target to achieve climate neutrality at least before 2050 is, for the chemical–pharmaceutical industry, quite a challenge as it is one of the highest CO_2 (and equivalents) generating industry by a chemical reaction thermodynamics definition [1,2]. However, as the objective and timeline is politically set, the key-question is how to achieve that technologically [3–6]. Here, chemical and biological process engineering methods have to propose solutions that have to take total mass and energy as well as GWP (global warming potential) balances into account under the constraints of being further-on in the world market competition. Therefore, COGs (cost-of-goods) vs. GWP process-related product comparisons have proven to be of aid for valid decisions [3].

It has to be acknowledged that the Germany chemical–pharmaceutical industry has moving targets worldwide by competing with state-ruled and financed or subsidies industrial systems such as the US-market (US first) and China's (MIC 2025), among others. The chemical–pharmaceutical industry is, in Germany, the third largest branch after automotive and mechanical engineering, which leads to a massive contribution on employment, tax and well-being in society [7]. The German chemical–pharmaceutical industry is the third-largest worldwide in that specification [8]. Germany contributes in total only to about less than 2% to worldwide-GWP CO_2 equivalents while being the 3rd largest economy worldwide [9]. In Germany about 1/3 GWP is related to industrial manufacturing while the chemical–pharmaceutical industry contributes to about 24% to that part, after steel and cement industries being again on position three. The German ChPI (chemical–pharmaceutical industry)-branch associations [10] have demonstrated and explained the substantial contribution of the German chemical–pharmaceutical industry the last decades in doubling productivity while cutting GWP by half at the same time spans [11].

Recent studies [10,11] point out that the politically decided energy change in Germany would have to be financed with about EUR 1 trillion. [12], and that the chemical–pharmaceutical industry does need about EUR 50 billion. additional investments as well as about 650 TWh green power [13]. This is in relation to the existing 250 TWh green power in Germany at the moment, and taking into account that solar and wind power facilities are almost not much to be increased in Germany any further, this is quite a specific challenge [14,15]. Nevertheless, Germany has always been a net-energy importer. Therefore, the question is how to generate for the total concept of a climate neutral world enough green power and how to close the main component recycles.

2. Section-Coupling and World Scale Competitiveness

To discuss that question technically and to point to any solution strategies, some basic constraints have to be defined a priori due to basic fundamental chemical–physical laws, pre-existing knowledge over the decades of process engineering and the many fold approaches worldwide:

- In Germany a manifold of even sometimes differing studies is available based on different approaches [16–21]. Most of these studies have to be ranked as type of first feasibility study in engineering theory [22]. Therefore, they need to be followed by experimental feasibility such as piloting and economic evaluation as well before being considered by investors for large scale investment. Some piloting studies are made [23,24]. It has to be taken into account that other regions are advanced, e.g., Japan's H_2 decision [25], Arabian region (solar power to x) parks [26–29], China [30] and the US [31] in either a piloting or industrial scale.
- Mass streams (jato) with energy content (GJ/ton) and GWP (CO_2eq/to) potential have to be considered always together and in total.
- Any energy and mass conversion has to be limited to its absolute minimum, as any additional step causes massive reductions in efficiency factor, which is equivalent to non-competitive waste and loss of money. Here, 1–2 steps is a limitation already known [32].
- Energy storage of green power is a challenge still unsolved [33–35]. However, this has always not been a task for chemical–pharmaceutical manufactures but for their energy suppliers, to whom the performance of energy supply reliability they pay their price, e.g., Arabian consortia solve that by financing solar power parks owned by the state and taking back for about 10–15 years defined energy amounts at guaranteed prices [36–39] at about a factor of 1/10 less than in Europe/Germany. Solving that, investors do like to take, in general, no risks.
- The magnitude of investments needs for the total technology circle in any branch now politically demanded are the largest in history ever and are therefore not to be covered without private investors. State money alone would cause deflation and unacceptable societal shifts by economic instability [40].

- New business concepts are needed. Non-calculable risks are taken by the state but financed by private investors, as in history before at any new technology cycle [41,42].
- Subventions of state should be limited to competitive products and technologies for being sustainable for society and being refinanced by taxes, employment and net-gross-product. Lessons learned from biogas, biodiesel and bioethanol must be avoided as in a magnitude, which is now discussed as the technology cycle; it is totally unrealistic to sink that money without payback as well.
- Some technologies and their competitive scales have already been approved and decided upon by others:
    - H_2 electrolysis is realized in scales 20–25 MW up to, recently, 100 MW [43].
    - H_2 mobility is focused on in, e.g., Japan, whereas, e.g., German automotive companies have differing strategies [44–46].
    - Sun fuels are an additional carbon source to be designed. The tank vs. plate discussion as well as huge regional agricultural mono-cultures lacking biodiversity have caused society to deny those approaches, and [47] biomass is regarded as too valuable for combustion; either nutrition or raw materials are much higher-value products. Growing world populations need land mass for nutrition at first.
    - Only 5% of worldwide oil is utilized for the chemical–pharmaceutical industry as its carbon feedstock needs. Therefore, it will be the last branch that gets oil as feed due to its high value generation and satisfaction of societal needs [48].
    - Fuel cells have suffered from efficiency factor loss due to additional conversion and unacceptable operation times for decades [49].
    - Green (solar and wind) power to x (chemicals) is based on mostly already-approved large-scale technology. Nevertheless, electric powers storage is not solved appropriately efficiently [50].

World-scale plants have proven their economy of scale benefits for decades [22]. Thus, small-scale, decentralized plant operations are not competitive.

- The cost of green technology conversions, additional not-refinanced investments and factor 3 higher COGs [51–54], an estimated 10- maximal optimistic 30% improvement by operation optimization, still leaves worldwide uncompetitive products. This would lead to the following approach: carbon feedstock has to be priced up. However, as a consequence, this would increase living costs to unacceptable limits.
- Moreover, such pricing taxes would cause natural counter-reactions and differences by state subsidies, e.g., CO_2 certificates in Germany are targeted to about 100 EUR/ton, whereas in the EU they are 50 EUR/ton, and in China 3–5 EUR/ton is discussed, causing unbalanced competition [55].
- Therefore, CO_2-free certifications for worldwide non-competitive processes and products would cause the taxpayer to finance that as well, which would cause unacceptable increases of living costs again.
- No additional CO_2 has to be generated additionally as feedstock; only thermodynamically unavoidable CO_2 generation by combustion and chemical conversion reactions (such as cement) will be acceptable, but this CO_2 cycle has to be closed as far as possible by generating, e.g., methanol.
- CO_2 captured for recycled carbon sources from gas effluents does need about 2 GJ/ton in any amine absorption/desorption process, which is the standard at the moment [56,57]. There are feasible, but quite low, efficiency factors and additional demands for still-rare green power.
- MeOH (methanol), sun fuels or any other carbon source should be avoided for combustion due to CO_2 generation. Here, at the moment ammonia is seen as an alternative, whereas Denox-processing has been feasible for decades [58,59].
- Methanol from CO_2 with green power H_2 via electrolysis is used as raw material for, e.g., polymer synthesis routes [60].

- The polymer manifold has to be limited to few minimal necessary main classes, such as perhaps five (PTFE, PE, PET and Polycarbonate as well as MDI/TDI foams.) Specialties will be needed but have to be limited and their recycle pathways established [61–65].
- Any product design fit for recycling has to be established (Figure 1), which is technologically a challenge. Even recent new technology being green lacks that: wind generation plants could not be recycled efficiently (to individual, non-standardized metal with GRP (glass fiber reinforced plastic) construction), and their pressed fiber plastic matrices do not even burn in WIPs (waste incineration plant).

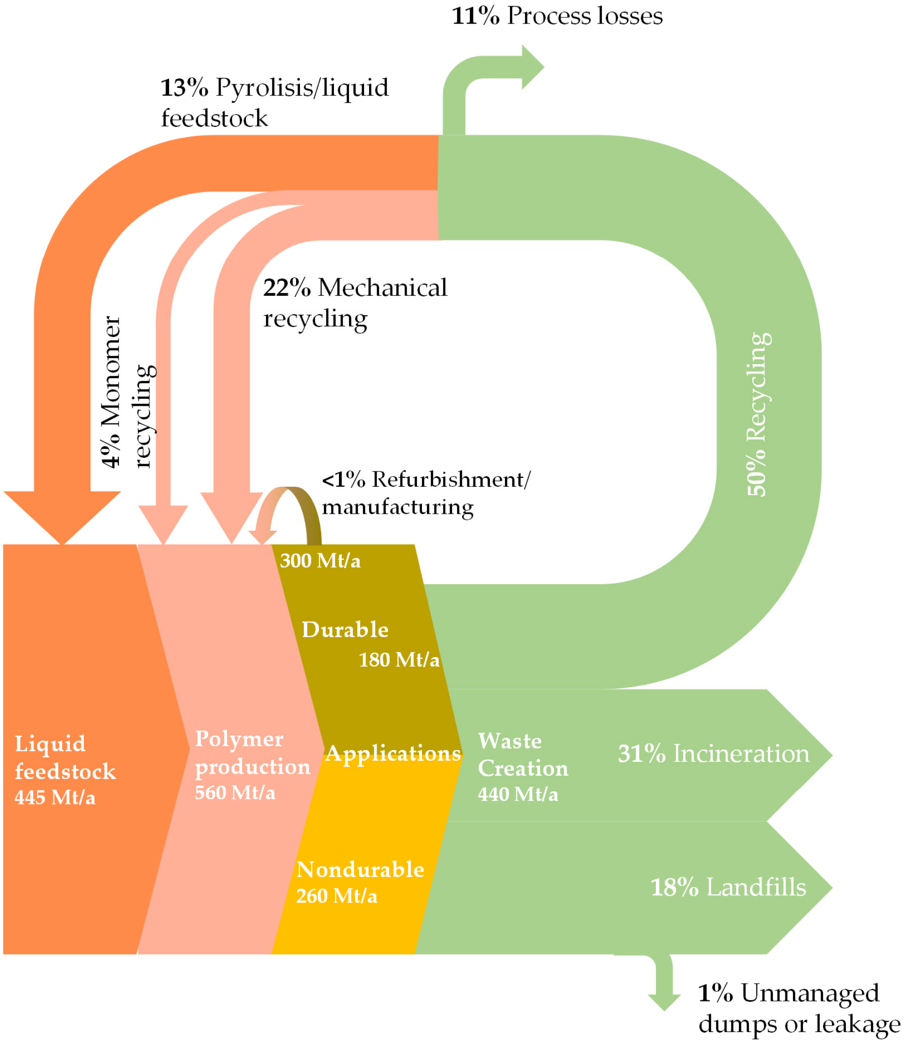

Figure 1. Global waste polymer flows 2030 at a recycling rate of 50%. Data from [66].

- Section coupling for energy on different temperature levels and electrical power as well as recycle streams have to be considered, e.g., at the moment, the cement industry takes municipal waste from WIPs to improve their GWP balance, but that leaves GIPs in under-load operation, inefficiently.
- Any long transportation has to be avoided, but a preferred main few liquids and gas mass streams should be summarized in pipelines such as CO_2, H_2, MeOH and ammonia for world-scale plants being competitive on the world market.

In contrast to other studies, the total part from total energy demand of 80% of ChPI is process heat (Table 1) [67]. If carbon sources are totally avoided for combustion towards process heat, then about 450 TWh of 650 TWh need to be substituted by ammonia. A CO_2 source in combustion is substituted as well as any not-highly-efficient heating by electric power.

Table 1. Process heat (excluding steel and cement industry) in 2050 [67]. HT (high-temperature); MT (mid-temperature); LT (low-temperature).

	HT Heat	MT Heat	LT Heat
Biomass	72%	17%	26%
Electricity	-	42%	51%
Methane	-	-	-
Waste	-	41%	16%
Hydrogen	22%	-	7%
Others	6%	-	-
Sum	353 TWh	77 TWh	53 TWh

The figures of the VCI/Dechema study could be comprehended by the authors [10]. The technologies needed such as H_2 electrolysis by green power (wind and solar) and N_2 by air separation towards ammonia as a main carbon-free combustion source via Haber–Bosch processing and MeOH as the central single basic carbon source chemical via Fischer–Tropsch are chosen. As a resume, all the technologies needed for such a change are already existing and technologically approved over decades. In addition, CO_2, once generated, is to be captured via amine absorption processing and recycled towards Fischer–Tropsch. To gain economy, an economy of scale is necessary. World-scale processing is state-of-the-art for all those processes. To supply those, a pipeline network of CO_2, MeOH, H_2 and N_2 as well as NH_3 is needed as infrastructure by modifications of existing pipelines (compressors and valves) as well as some enlargements, of course.

3. Advanced Circular Economy

The Clausthal University of Technology has focused, with its "Advanced Circular Economy" mission statement, on such solutions. The declared research focus of the TU Clausthal is (Advanced) Circular Economy. When looking at the distribution within the entire Green Economy, Figure 2, it is obvious that a group is needed within its own ranks that opens the door for the innovations that are known to take place mostly at professional interfaces.

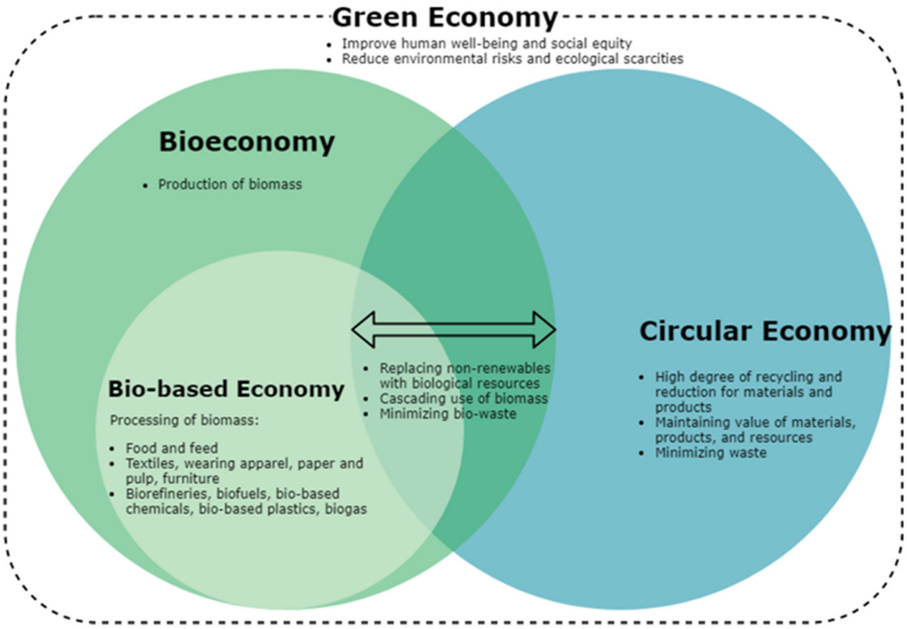

Figure 2. Relations between bio-, bio-based, green and circular economies [68].

This requires interdisciplinary cooperation in the long term. In order to achieve this, a working group at the TUC is therefore urgently needed as a direct professional contact on-site and door opener for collaborations from the field of the adjacent bioeconomy.

- Urban mining is the recycling of rare elements such as Nd (electro motors magnets), Li (batteries) and rare earth elements (electronics) and has to be industrialized and technologically optimized to be green, sustainable and economic [69–72].
- Bio-refinery concepts are only suitable with waste streams in cascade utilization and recycling strategies, as no agricultural space is free for energy or carbon source generation, which should anyhow be avoided [47,73,74]. As mass products lack efficiency with huge land killing potential [75–77], in contrast, specialties utilizing the plants' own synthetic power for complex molecular structures should be used [78]. Here, GWP vs. COGs analysis, Figures 3 and 4, balances it as economically feasible [3]. The general rule is obvious, that it is inefficient by mankind to destruct at-first complex molecular structures made by nature already in order to afterwards generate new molecular entities from scratch with complex synthesis routes (see Figure 5) [79,80].
- Bio-based-world approaches include enzymatic instead of chemical synthesis routes. Improvements are still many fold [81–83]. Synthesis does need new catalysts and intensified green approaches such as electrochemistry and plasma ionization, even on the standard processes such as Haber–Bosch [84–89] and Oswald [90–93].
- Sustainable material needs are manifold. Pointed examples may be the aerospace industry, with high technology and high performance at lowest weight-composite materials—e.g., even general workhorse bisphenol A has to substituted due to REACH demands [94–103].

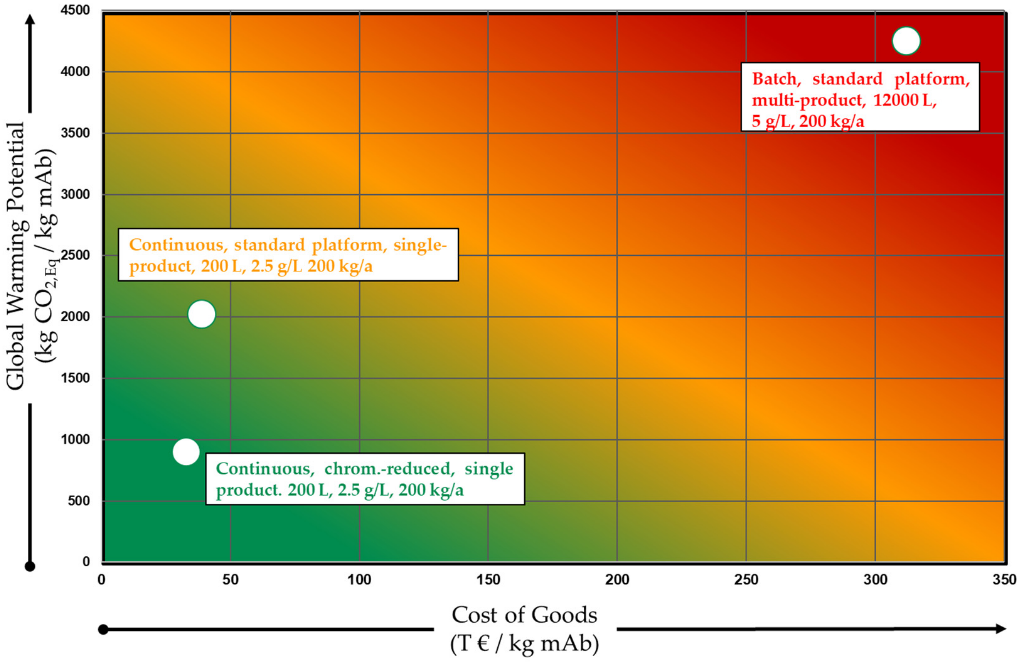

Figure 3. Biologicals GWP (global warming potential) vs. COG (cost of goods) portfolio. mAb: monoclonal antibody.

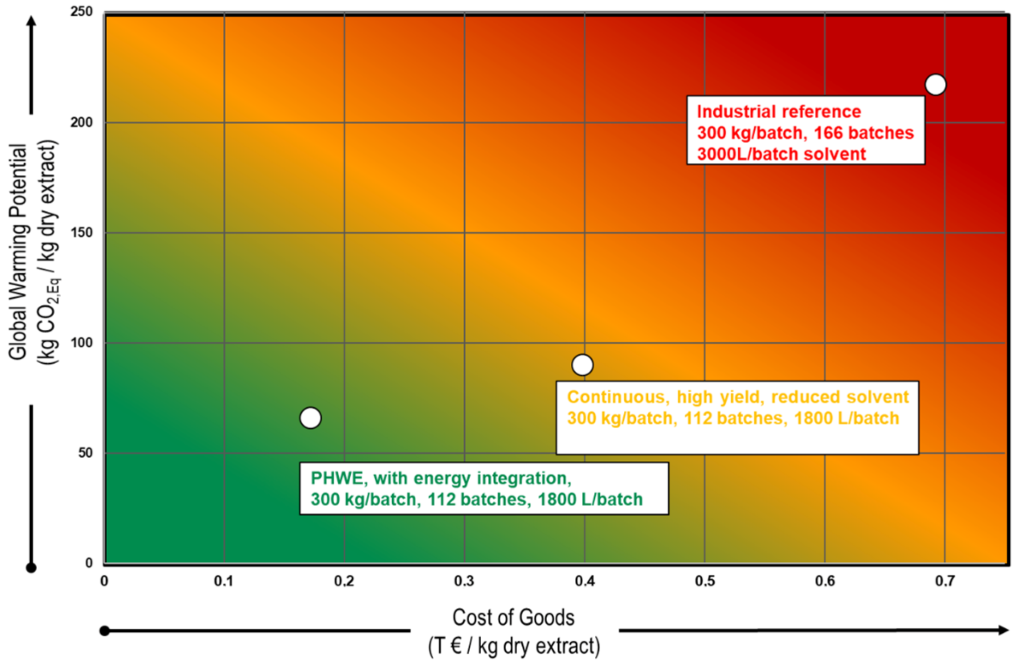

Figure 4. Botanicals GWP (global warming potential) vs. COG portfolio.

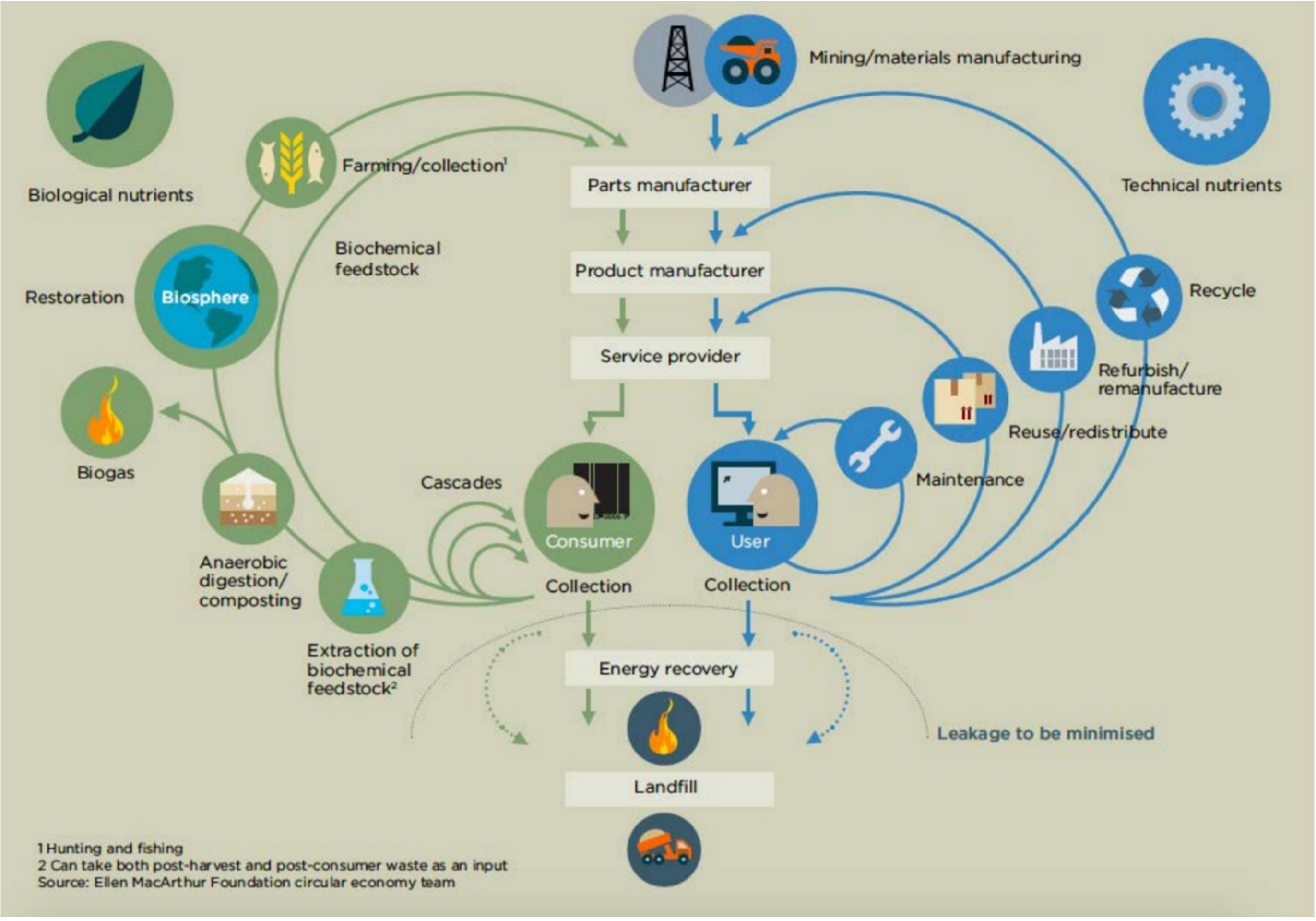

Figure 5. Illustration of cascade use within the circular economy [104].

4. Germany Chemical–Pharmaceutical Industry Conception for Climate Neutrality

As a basis for any discussion, the general balances regarding main key-component mass streams, energy content and supply as well as the GWP equivalent are summarized in magnitudes as estimations or based on literature values [10] and pointed out for any conclusions (see Tables 2 and 3).

Studies have shown that up to 80% of the total energy demand in the German chemical/pharmaceutical industry is accounted for by process heat at different temperature levels [67]. Contrary to a multitude of concepts, the climate-neutral provision of this energy demand is to be provided by the combustion of ammonia instead of green electricity in this work. The total energy demand of the German chemical/pharmaceutical industry is calculated to be 3024 PJ (840 TWh) in 2050. This figure is found in a similar order of magnitude in many studies and is thus assumed to be a robust base load scenario [10].

With a lower heating value of 5.2 kWh/kg, 129 million jato of ammonia is required to provide 672 TW (80% of total energy demand). The input quantities of electrolysis hydrogen and nitrogen from air separation required for this amount to 23 million jato (H_2) and 109 million jato (N_2), respectively. The total energy requirement (including water electrolysis) is taken from the literature and amounts to 10.89 MWh/t NH_3 [10]. The calculated electricity demand for the supply of ammonia from the Haber–Bosch process is 5066 PJ (1407 TWh) accounted to the industrial energy section, resulting in a magnitude of 10 world-scale Haber–Bosch plants with an estimated CAPEX of about EUR 5 bil. [105].

Table 2. Inlet mass and energy streams of German Chemical–Pharmaceutical Industry in 2021.

Resource	Category	Primary Energy	Resource	Sum
Electricity	Mio jato	-	-	0.0
	PJ	189.4	-	189.4
	TWh	52.6	-	52.6
	GWP Mio t	21.5	-	21.5
Natural Gas	Mio jato	7.2	3.2	10.4
	PJ	302.4	133.6	436.0
	TWh	84.0	37.1	121.1
	GWP Mio t	16.9	-	16.9
Naphtha	Mio jato	1.0	13.3	14.3
	PJ	43.2	556.9	600.1
	TWh	12.0	154.7	166.7
	GWP Mio t	3.2	-	3.2
Hard Coal	Mio jato	0.4	0.2	0.5
	PJ	10.8	4.4	15.2
	TWh	3.0	1.2	4.2
	GWP Mio t	1.1		1.1
Brown Coal	Mio jato	0.3	0.2	0.4
	PJ	8.6	4.4	13.0
	TWh	2.4	1.2	3.6
	GWP Mio t	0.9	-	0.9
Others	Mio jato	5.6	-	5.6
	PJ	165.6	-	165.6
	TWh	46.0	-	46.0
	GWP Mio t	18.8	-	18.8
Renewable Resources	Mio jato	-	2.6	2.6
	PJ	-	-	0.0
	TWh	-	-	0.0
	GWP Mio t	-	-	0.0
Sum	Mio jato	14.6	19.4	34.0
	PJ	720.0	699.2	1419.2
	TWh	200.0	194.2	394.2
	GWP Mio t	62.2	-	62.2

Table 3. Inlet mass and energy streams of German Chemical–Pharmaceutical Industry in 2050.

Resource	Category	Primary Energy	Resources	Sum
Ammonia	Mio jato	-	-	0
	PJ	2465	-	2465
	TWh	685	-	685
	GWP Mio t	-	-	0
Fossil Resources	Mio jato	-	-	0
	PJ	74	-	74
	TWh	21	-	21
	GWP Mio t	-	-	0
District Heating	Mio jato	-	-	0
	PJ	87	-	87
	TWh	24	-	24
	GWP Mio t	-	-	0
Renewable Fuels	Mio jato	-	-	0
	PJ	124	-	124
	TWh	34	-	34
	GWP Mio t	0	-	0
Waste Plastics	Mio jato	3	-	3
	PJ	70	-	70
	TWh	19	-	19
	GWP Mio t	0	-	0
Biomass	Mio jato	11	-	11
	PJ	205	-	205
	TWh	57	-	57
	GWP Mio t	0	-	0
CO_2	Mio jato	-	55.00	55
	PJ	-	-	0
	TWh	-	-	0
	GWP Mio t	-	-	0
Sum	Mio jato	14	55	55
	PJ	3024	0	3024
	TWh	840	0	840
	GWP Mio t	0		0

If a 100 MW world-scale electrolysis plant with an investment of EUR 70 million and a capacity of 16 thousand tH_2 is used as a reference plant for hydrogen electrolysis [106], this results in 1438 total plants and an investment of EUR 101 billion for the provision of the necessary hydrogen in the Haber–Bosch synthesis.

In the case of nitrogen, a world-scale air separation plant with an investment of EUR 200 million and a capacity of 3.24 million metric tons of N_2 is used as a reference [107]. This results in 34 total plants and an investment of EUR 7 billion for the provision of the necessary nitrogen in the Haber–Bosch synthesis.

The overall—and outlet—mass and energy estimations of the German Chemical–Pharmaceutical Industry in 2050 are graphically shown in Figure 6.

The provision of carbon sources as a resource stream for synthesis reactions in the chemical/pharmaceutical industry is the second fundamental pillar in ensuring productivity, along with the provision of energy. It is calculated in line with other studies with 55 million jato of carbon dioxide equivalents for 2050 [10]. In this concept, this is to be provided by a closed loop consisting of Fischer–Tropsch methanol synthesis as input material for plastic production as well as its recycling and about 80% combustion [66]. Other integration concepts include the use of carbon dioxide produced in the cement, steel and waste incineration industries [18,108].

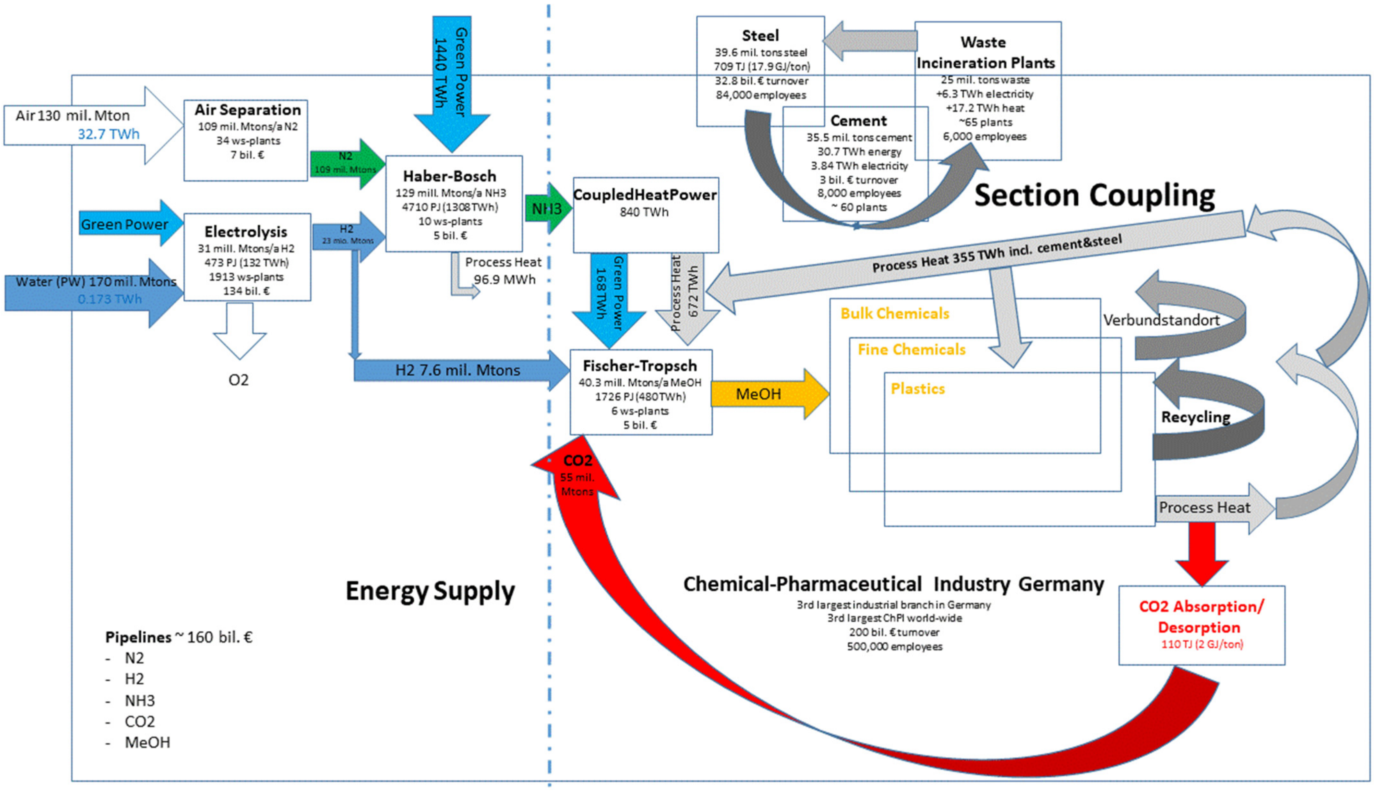

Figure 6. In- and outlet mass and energy estimations of German Chemical–Pharmaceutical Industry in 2050.

To provide 55 million CO_2 equivalents, 40.3 million metric tons of methanol are required. CO_2 is captured by classical amine absorption with about a 2 GJ/ton energy demand for desorption [56,109,110]. The amount of water required for hydrogen electrolysis amounts to 128 million jato. The electricity demand is calculated to be 1726 PJ (480 TWh) using literature data (9.52 MWh/tMeOH) [10]. To calculate the funds required for this, a plant with an investment of EUR 900 million and a production capacity of 6.913 million jato of methanol is used as a reference [111]. This results in a total number of six Fischer–Tropsch production plants and a total investment of 5 billion EUR.

The supply of the produced gases (hydrogen, nitrogen, carbon dioxide) and methanol is implemented through a pipeline network. Two documented cases are used as references. One is the Nabucco pipeline with an investment of EUR 8 billion, a total length of 3300 km and a capacity of 31 trillion m^3/year [112]. On the other hand, a study conducted by PTJ, in which a hydrogen pipeline network including infrastructure with a total investment of 23 billion EUR, the total length was 48,000 km with a capacity of 5.4 million t/year [113]. If a total length of 5000 km is considered necessary for each of the gases produced (hydrogen, nitrogen and carbon dioxide) as well as methanol, this results in a necessary investment of EUR 159 billion.

5. Discussion and Conclusions

The chemical–pharmaceutical industry in Germany has made its homework, for 6–7 decades after oil crises in the 1970s and the environmental crises in 1980s, to double productivity at its concurrent GWP reduction by a factor of four—this is already a very good efficiency factor in ChPI manufacturing (Figure 7).

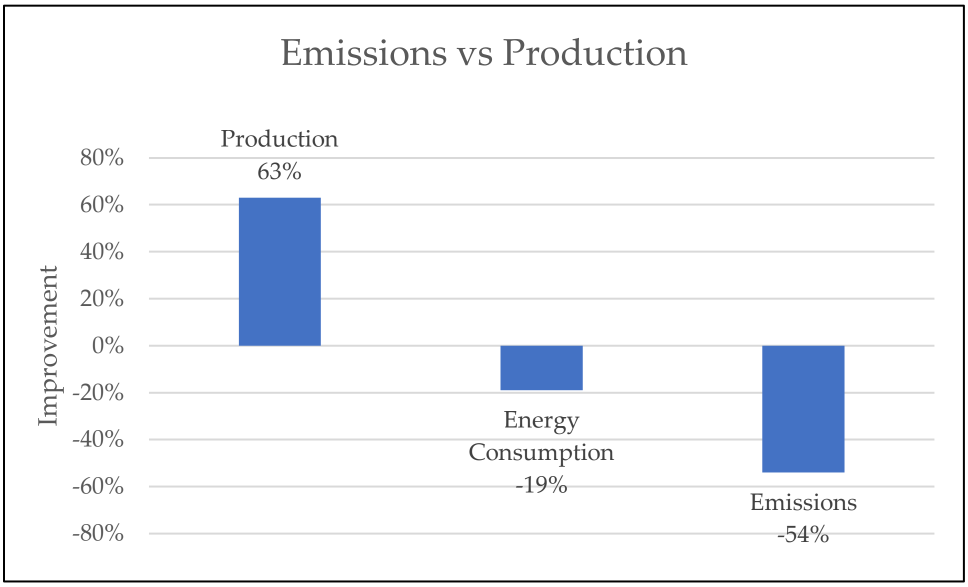

Figure 7. Development in the German chemical/pharmaceutical industry (1990–2019) [114].

Comparing statistical data [115,116] further-on of main GWP-emitting countries based on their efficiency productivity factors such as GWP CO_2 eq in relation to export bil. EUR/a or (gross national product) GNP billion. EUR/a, thin it is obvious that those 4–5 countries being responsible for more than 60–70% of world GWP emission are magnitude factor 10 less efficient in manufacturing than, e.g., Germany today. Basic logic points out that any efforts should at first with priority be taken to increase those countries to the actual level because of having the highest result with acceptable and feasible efforts. Even so, such a reduction of about 70% of GWP emission worldwide reduced to about 7% would solve the climate neutrality at once, at least in a magnitude.

In addition, doing that, Germany would have, already, an existing market for existing technologies. Any fundamental marketing rules emphasise to do this at once to regain the already-made investments and only afterwards try to sell the technologies to be developed with the aid of the actual cash flow from this business. Any hopeful shifts to later market prognoses of any to-be-developed innovative climate-neutral technologies therefore have no fundamental social-economic basis. The additional investments discussed do have a historic dimension. Nevertheless, the search for non-useful subsidies has started in Germany and budgets in magnitudes of few EUR hundred billion. per year [117–122] to cover those budgets needed seems to be concluded, taking into account that the new infrastructure in EUR 200–300 billion. additional investments as summarized before has to be under full operation within a 30-year timespan. The 2018 spontaneously estimated EUR 1–1.2 trillion. additional investment needs postulated have been discussed widely [12,123–125].

Nevertheless, the magnitudes at stake are so huge that an appropriate technology has to be chosen, as the budgets may even only reach once. Digitalization points to being one of the key-technologies for efficiency [126–128]. In a non-natural resource-rich country such as Germany, this seems to be an appropriate solution, as human education and training ready for even more complex technologies is feasible and a competitive advantage. All the process integration, intensification and section coupling demanded to gain the objective of climate neutrality cause much more complex and higher interconnected interferences for plant operation to be covered without any safety losses [129].

The status of the Germany Chemical–Pharmaceutical industry has been analyzed by mass flow, energy and GWP balances, and based on that a consistent concept to gain climate neutrality is proposed. Unnecessary new entities have to be avoided, and the focus has to be on the main components; the number of key-components has to be reduced, and any carbon sources are to be avoided.

Recycling and product design for recycling is a precondition, as well as no combustion of carbon sources but instead, e.g., ammonia. World-scale plants are necessary for world-wide competitiveness, which denies the benefit of decentralized small-scale plants and which causes pipelines of main key-components such as H_2, CO_2, MeOH and ammonia. The internal CO_2 cycle has to be closed into MeOH by Fischer–Tropsch processing as a single main carbon source bulk chemical by Fischer–Tropsch processing and further-on into polymer processes, which will lead into the CO_2 recycling cycle again [130–132]. The chemical–pharmaceutical industry needs external energy of 5066 PJ (1407 TWh) for Haber–Bosch processing including H_2 electrolysis and air separation (N_2). However, Germany has always been an energy importer, so why should it not be in the future?

Nevertheless, solar and wind energy in Asia and Arabian countries will directly implement air separation to N_2 and Haber–Bosch towards ammonia, which could be transported by classical logistics quite more easily than electric power or H_2—which seems to be limited to about 200 km pipelines [133]. Therefore, the risk for any (further) de-industrialization of the chemical–pharmaceutical industry in Germany is given if not focusing on higher value products manufacturing and technology for power-to-X to be sold. Bridge technologies, such as having carbon sources, should be avoided. Any investment or subvention not into world-market economic products is a waste of tax or investors' money.

As the mission is to save the planet, without the general economic welfare losses as pointed out before, the main fastest impact to reduce the world's climate gas emission is to transfer, e.g., Germany process technology efficiency to the four-six world's most-polluting countries. Based on that, there is no overemphasized haste for bridge technologies not being sustainable or deconstructing German industrial impacts by mid-term, non-valid, still carbon-sourced pathways.

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