CO₂ abatement economics - a practical view

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Abstract

The present studies aim at bridging between sophisticated scientific research and the broader society. The present work examines the economic stimulus required for the intended transition from fossil sources to renewables. To estimate cost competitiveness in energy supply from the various primary sources, a practicable, yet comprehensively levelized and fully described framework is applied. The estimates are compared with previous field reports and projection studies. In result, renewables have principally become cost-competitive to fossil sources in energy production. The overall transition to renewables is found to potentially come cost-neutral. It is argued that no special discounting be necessary if carbon emissions reduction is established in the order of 3 %/year (year-on-year) for about 100 years. Regarding transmission belts, it is advocated to cap plain CO₂ pricing at 50 \$/tCO₂ and moreover, to emphasize distributive and differentiative regulation when considering free-market-based mechanisms such as CO₂ pricing and carbon certification/crediting.

1. Introduction

It has been widely accepted that the atmospheric CO₂ concentration significantly influences Earth's near-surface temperature. It also appears undisputed that humankind has sent vast amounts of CO₂ into the atmosphere during the recent past. In society, disagreement has persisted on the actual effect of emissions onto temperature. As a bridge to the dispute, society may assume the risk of the human emissions to significantly impact worldwide temperatures and thus climate.

Then, a logical approach is to first identify the main emissions sources; second to search for appropriate risk mitigation mechanisms; and third, to assure the prerequisites in place for the mitigation potentials to successfully become realized, amongst others in economic terms. To the first, the identification of the emissions sources is considered well set. The present studies concentrate on carbon released in form of CO₂, where the major emissions sources are energy supply (heat and electricity), transportation, industrial processes including cement manufacture, and land use. To the second, also the identification of the potential mitigation measures is considered well set within the present studies. To the third, the economic transmission belt for the emissions reduction measures seems under discussion. As favored mechanisms, dedicated carbon taxation (CO₂ pricing) and carbon certification/crediting have emerged, entailed by the inherent question about the appropriate CO₂ price. The present article aims at identifying the driving terms behind a required CO₂ price with the hope that such insight may foster a broader consensus within society.

Following the focus of the societal discussions, the present article first concentrates on the energy sector and then expands to the entirety of emissions and their abatement. For the energy sector, the essential economic characteristics are identified to understand the relative competitiveness of the various energy production techniques to first order. With this aim, a practicable, yet comprehensive, and fully documented estimation scheme is presented for the levelized energy production costs, and is applied to a

variety of energy production techniques. The results shed light on the competitiveness of the various techniques and in turn, lead to the proposition of a differentiating and redistributing CO₂ pricing scheme. These first-order considerations are then compared with previous practice reports and projection studies. Finally, the appropriate discount rate related to climate mitigation is discussed.

With the focus on the driving terms, the values used in the present studies are considered representative for world (or widely common) averages, the same applying to the results. Before this background and for conciseness, sources of input values are only selectively listed. Energy production is divided into supply of electricity and heat, provided by direct combustion and non-combustion. Electricity production is considered for coal, natural gas, wind, photovoltaic (PV), and biomass CHP (Combined Heat and Power); heat production for coal, oil, natural gas, and non-CHP biomass; analysis of electricity from biomass CHP presumes simultaneous utilization of the produced heat.

2. A Practical View On Energy Supply Economics And Co2 Emissions

The applied estimation scheme for the levelized energy generation costs is entirely defined by equation set (1); its detailed application is explicated in the appendix. Total costs (*cost*) are aggregated from costs for capital (*cap*), operations and maintenance (*om*), feedstock (*fuel*), profit (*profit*), land (*land*), systems integration (*net*), regulatory levies and subsidies (*reg*), and fossil replacement preponing (*rep*). Capital (*cap*) is assumed provided by credit, thus composed of investment redemption (*inv*) and interest (*int*), complemented by decommissioning costs (*decom*). Operations and maintenance (*om*) are composed of variable (*om_{var}*) and fixed (*om_{fix}*) components. Profit (*profit*) is related to the aggregate of *cap*, *om*, and *fuel*; in electricity production, these costs plus profit are interpreted to reflect the feed-in tariff required for profitability. Regulation costs (*reg*) are subdivided into emissions tax (*emis*), all other tax (*tax*), and subsidy (*sub*); emissions tax (*emis*) is based on combustion emissions levies (*comb*) and carbon sequestration credits in the case of biomass (*sequ*).

$$\begin{aligned}
 cost &= cap + om + fuel + profit + land + net + reg + rep, \\
 cap &= inv + int + decom, om = om_{fix} + om_{var} \\
 inv &= C_{eff} / \tau / H_{eff} \quad C_{eff} = C_{inst} \cdot (1 + e_{self}), int = C_{eff} \cdot i / H_{eff} \quad H_{eff} = H_{max} \cdot \varepsilon \cdot \lambda, H_{max} = 24 \cdot 365 \\
 &\text{h/year,} \\
 decom &= (1 + \delta) \cdot inv, om_{fix} = inv \cdot o, fuel = P_{mat} / E_{mat} / \varepsilon, profit = (cap + om + fuel) \cdot \pi / (1 - \pi), \\
 land &= p_{land} / L, L = (yield \cdot E_{mat}) / \varepsilon \cdot (1 + e_{self}), reg = emis + tax + sub, emis = comb + sequ, \\
 sequ &= P_{CO2} \cdot S / L, comb = P_{CO2} \cdot CO2_{mat} \cdot (1 + e_{self}) / \varepsilon \cdot (1 + c_{self}),
 \end{aligned} \tag{1}$$

Inflation has been taken into account for accumulation of decommissioning reserves; else inflation is disregarded, with the note that energy generation costs relatively strongly reflect inflation for the fuel-

intensive fossil and biomass sources while wind and PV exhibit rather inflation-independent production costs (within systems lifetime).

In the further description, dedicated land costs for biomass (*land*), emissions tax (*emis*), subsidy (*sub*), and replacement costs (*rep*) are optionally considered. Effects from unmentioned contributions are regarded subsumed within the presented framework, e.g. from grid loss.

Energy self-consumption during development, construction, operations, and decommissioning is considered supplied by the respective system itself, leading to required higher effective capacity than installed, with respective costs C_{eff} and C_{inst} . Analogously, the regarded CO₂ emissions reflect life-cycle emissions ($CO2_{mat}$ expanded by e_{self} and c_{self} for the fraction of self-consumed energy and analogous self-emissions, respectively).

Further variables in equation set (1) are:

τ production system (economic) lifetime,

H_{max} total number of hours per year,

ε energy conversion efficiency,

λ fraction of effective full-load operations,

δ ratio of decommissioning costs to construction costs *inv*,

i interest rate,

o ratio of fixed operations and maintenance costs to investment *inv*,

P_{mat} fuel price,

E_{mat} raw material energy content (net calorific value),

π profitability ratio,

p_{land} land price,

yield harvest yield,

P_{CO2} CO₂ price,

S carbon sequestration rate,

$CO2_{mat}$ CO₂ from raw material carbon (direct combustion).

2.1 Electricity production

For electricity production, the effective capacity cost (C_{eff}) is of the order 1,650 \$/kW for coal until the recent past, natural gas, onshore wind, and PV; coal may have increased to 3,600 \$/kW for new plants under conception [1]; offshore wind and biomass CHP at about 5,650 \$/kW (\$ for US\$ throughout the present article).

The fraction of effective full-load operation is taken as constant 95%, except for wind offshore, onshore, and PV with 38%, 24%, and 14%, respectively. Efficiency of conversion from material energy content to produced electric energy (ε) is 42% for coal and natural gas, 100% for wind and PV, 18-30% and 80% for biomass in simple and CHP mode, respectively. It is noted that consideration of 80% for biomass CHP presumes simultaneous heat utilization and electricity generation. The preceding efficiency figures lead to effective full-load hours per year (H_{eff}) of about 3,400 h/year for coal, natural gas, and offshore wind; 2,100, 1200, 2500, and 6700 h/year for onshore wind, PV, biomass simple and CHP, respectively.

Related to material energy content, considered fuel prices are 0.7 and 1.4 ¢/kWh_{mat} for coal (corresponding to 42 and 81 \$/t in electricity production and commercial usage; ¢ for US¢), 2.5 ¢/kWh_{mat} for natural gas (corresponding to 320 \$/t as medium price between long-term lows and intermediate price peaks), furthermore 1.8 and 3.6 ¢/kWh_{mat} for biomass (the lower value corresponding to typical 75 \$/t for dried mass, the higher value to 150 \$/t of alternative biomass [2]).

System integration costs are considered as 2.2, 5.1, and 1.5 ¢/kWh for onshore and offshore wind, and PV, respectively [3] (kWh relating to produced energy throughout the present article).

A sensible approach for the transition from fossil fuels to renewables certainly is to switch off fossil electricity plants at the end of their economically calculated (depreciation) lifetime. Assuming an average calculated lifetime of 30 years and a decision that all fossil plants be switched off within 20 years from a given point in time, the economic burden is estimated in first order to about 1% of all further production costs (details not described) and therefore, is disregarded in the further analysis.

In the present analysis, lifecycle CO₂ emissions per generated electricity are taken as 820 and 530 gCO₂/kWh for coal and natural gas, respectively; 30 and 40 gCO₂/kWh for wind and PV; -100 and -40 gCO₂/kWh for biomass simple and CHP, respectively, composed of 80 and 30 gCO₂/kWh from feedstock production plus -180 and -70 gCO₂/kWh from sequestration with (conservative) net sequestration of 0.6 MgC/ha/year (cf. [4]).

Based on the preceding figures without CO₂ pricing, electricity production costs are determined as 14 ¢/kWh for offshore wind at the high-end. The minimum production costs are 5-6 ¢/kWh for existing coal plants (low-value set for construction and fuel costs) and onshore wind. In between are the production costs of 8-10 ¢/kWh for all other generation types, except for non-CHP biomass electricity production with exceeding 15-24 ¢/kWh at 18-30% conversion efficiency. The latter costs demand preclusion of biomass

utilization solely for electricity production, not least also in view of the disproportionate waste of scarce resources.

Raising biomass deployment to large scale may require land costs to be taken into account. Based on 600 \$/ha/year (corresponding to agricultural income substitution) and an average dry-mass (DM) yield of 10.5 MgDM/ha/year, the land price is 1.4 ¢/kWh_{mat} related to the material energy content and 1.8 ¢/kWh for biomass CHP-produced energy.

As part of the electricity generation market, existing fossil (particularly coal) plants offer electricity at marginal costs of 2 ¢/kWh. If this competitive advantage is to be counterbalanced via CO₂ emissions taxation, the CO₂ price needs to be about 90, 120, or 150 \$/tCO₂ so that the production costs of PV, biomass CHP (higher feedstock price, land costs included), or offshore wind equal the costs of marginal-cost coal operators, respectively. With the latter CO₂ levy, the production costs are 15-17 ¢/kWh for the marginal-cost coal and natural gas, as compared to 7-10 ¢/kWh for onshore wind and PV, and biomass CHP (higher feedstock price, no land costs, neither CO₂ levy nor carbon credit), offshore wind equaling coal. Relative to the fossil past in a bird's eye view, this represents an electricity price elevation of 8-9 ¢/kWh from fossil fuels and if all fossil sources were replaced by renewables, a price elevation of 3 ¢/kWh.

2.2 Direct heat supply

In the present studies, heating via direct combustion is considered for coal, oil, natural gas, and biomass. The considered effective installation costs (C_{eff}) range from 120 to 340 \$/kW for natural gas, coal, biomass, and oil (from low to high). For all, the fraction of full-load service per year is viewed as 10%, the energy conversion efficiency as 70%. From this, the number of effective full-load hours per year is 613 h/year. The fuel prices are taken as the long-term medium for natural gas and from the spot prices for the other feedstock, i.e. 3.0, 4.5, 2.5, and 6.7 ¢/kWh_{mat} for coal, oil, natural gas, and biomass, respectively (corresponding to 170, 556, 320, and 280 \$/t, the latter the spot market price for pallets).

The resulting energy production costs are 5, 7, 11, and 14 ¢/kWh for natural gas, coal, oil, and biomass. If biomass feedstock can be purchased at the medium price (3.6 ¢/kWh_{mat} or 150 \$/t in electricity production), the corresponding heat production costs are reduced to 9 ¢/kWh.

The life-cycle CO₂ emissions per delivered energy are 500, 420, and 320 gCO₂/kWh for coal, oil, and natural gas; for biomass, 34 from feedstock supply and -77 gCO₂/kWh from sequestration. With the above-mentioned CO₂ price of 150 \$/tCO₂, heat costs nearly double by 5-8 ¢/kWh for fossil fuels to 10-17 ¢/kWh (for comparison, heat costs from renewables electricity at about 10 ¢/kWh).

To estimate the related CO₂ emissions, it is assumed that all fossil fuel consumption in the sectors residential and commercial is related to heating. With the preceding emissions figures and energy consumption data (as used for [5], source references therein), fossil-based energy supply in the two sectors is composed of coal, oil, and natural gas by 11, 27, and 62%, respectively, the consumption-

weighted average resulting to 367 gCO₂/kWh. From the studies of [5], 7.4% of total global CO₂ emissions originate from the sectors residential and commercial, and a complete transition to renewables attains a CO₂ emissions reduction in the order of 92%. Thus regarding heat supply in these two sectors, the transition from fossil fuels to renewables bears an emissions reduction potential of about 7% off total global emissions.

2.3 Summing the results from basic economics and emissions analysis

A practicable, yet comprehensive and fully documented estimation method has been applied to the levelized costs of various energy production techniques. The major aim has been to examine previously published results for their reproducibility. Overall, the cost estimates align well with other publications (comparison details not presented). Furthermore, the influence of CO₂ pricing on cost competitiveness between the various techniques has been explored.

In production of electricity from various sources (coal, natural gas, wind, PV, and biomass CHP, the latter with simultaneous electricity and heat utilization), the basic metrics indicate energy production costs in rather wide spans: 6-10 ¢/kWh for most renewables (from low to high: onshore wind, PV, biomass CHP), topping at 14 ¢/kWh for offshore wind; 5-10 ¢/kWh for fossils (low to high: existing coal plants, natural gas, new-conception coal plants), the lower boundary decreased to 2 ¢/kWh by the marginal-cost generators. If offshore is to be competitive with the latter low costs and if CO₂-emissions taxation is the regulation mechanism of choice to balance competitiveness, the CO₂ price needed to be in the order of 150 \$/tCO₂. In this case, the electricity production costs are raised above familiar levels by roughly 8-9 ¢/kWh for the fossil sources and 3 ¢/kWh if these are replaced by renewables.

In direct heating, this CO₂ levy nearly doubles existing heating costs from fossil fuel which then approximately equal those from biomass – for a contribution to the total emissions reduction of approximately 7%. This certainly appears disproportionate and socially unjust. In conjunction with the wide energy generation cost spans for the various techniques, the necessity is indicated for differentiative and distributive regulation mechanisms instead of plain CO₂ pricing.

3. Example For Differentiative And Distributive Co Pricing

An example for a differentiating and redistributing CO₂ price mechanism is presented in this section, with the following characteristics. A CO₂ price of 50 \$/tCO₂ is applied to the life cycle emissions of all energy production but electricity production from natural gas. This CO₂ price equals a taxation on raw material calorific value of 1.7 ¢/kWh_{mat} for coal and 1.1 ¢/kWh_{mat} for natural gas, or on generated electricity of 4.1 ¢/kWh from coal, and on generated heat of 1.6-2.5 ¢/kWh from natural gas, oil, and coal (from low to high). From the taxation revenues, the renewables are subsidized per generated energy by 4.1 ¢/kWh, exempting onshore wind because of its already high competitiveness. This output-based bonus has

equal levelized cost effect if installation investment is subsidized by 48-55% for offshore wind and PV and by about 100% for biomass (no dedicated land costs).

As depicted in Figure 1, this example leads to comparable electricity production costs of 5-7 ¢/kWh for all technologies (coal at marginal-cost and natural gas at low fuel price; biomass with CHP) but for natural gas at medium fuel price and offshore wind with 9-10 ¢/kWh. Heat costs from direct combustion is estimated to 10 ¢/kWh for coal, natural gas at peak price, and biomass; 13 ¢/kWh for oil; and 7 ¢/kWh for natural gas at medium price. For electricity production, the example shows overall competitive costs; only natural gas at medium gas price and offshore wind appear less attractive. For heat production, biomass can cope with the costs from coal and natural gas at peak price, and exhibits a clear advantage over oil; heating with natural gas is generally still cheaper than all others, to about the same amount as electrical heating. For comparison with the 150 \$/tCO₂ before of plain CO₂ pricing, the presented differentiating example renders offshore wind competitive with marginal-cost coal at a CO₂ price of 74 \$/tCO₂. It is noted that all results of the present work are before taxes other than from CO₂ pricing.

Conclusion

For CO₂ pricing, an example of combined taxation & crediting is presented. The results exhibit the following characteristics. (i) It is shown that a differentiating levy & subsidy mechanism can hold energy prices at bearable levels and in turn, entailed inflation. – Present (fossil fuel-concentrated) heat costs are elevated by sound 2 ± 0.5 ¢/kWh; biomass obtains a cost advantage over oil of 3 ¢/kWh, natural gas generally produces 3 ¢/kWh cheaper than coal and biomass. – Electricity costs remain rather unchanged (in the future for coal, only marginal-cost generators left) facilitating overall smooth transition into the renewables future. (ii) The overall cost competitiveness between the various techniques ensures the market forces to support the transition from fossils to renewables. (iii) The continuing electricity supply from fossil fuel marginal-cost generators ensures sound transition and required backup. (iv) Biomass is cautiously promoted avoiding undesired risks, e.g. from land use competition.

4. Renewables Transition Economics

The costs of CO₂ emissions reduction and thus climate mitigation have previously been studied in abundance. The present work aims, inter alia, at sizing the stringency of frequent conclusions, e.g. huge capital needs, strong discounting, and CO₂ pricing. During the present studies, an extensive search has been performed through the existing literature for the various topics. However, detailed listing, reviewing, or statistical analysis is beyond the present scope. Consequently, the present description exhibits certain subjectiveness. Nevertheless, it is expected to deliver valuable insight. In this paragraph, the performed analysis is presented four-fold: looking first at field reports from actual projects; second at previous comprehensive projection studies; third at the potentially appropriate CO₂ price; and fourth, proposing a pragmatic view on discounting.

4.1 Transition costs from experience in the energy sector

While the preceding paragraph described a theoretical estimation procedure on the costs of energy production, the following lines present selected results of field reports. The focus is to size the economic stimulus required for the intended transition from fossil fuels to renewables.

Photovoltaic. According to [6] with reference to [7], currently commissioned projects of utility-scale PV considerably undercut the operational costs of coal energy plants with PV production costs at 7 ¢/kWh. This is confirmed by the global auction values where PV now falls below the range of new fossil-fuel power generation with PV at about 5 ¢/kWh [8]. – New PV plants are currently under conception anticipated profitable with 6 ¢/kWh feed-in tariff [9].

Onshore wind. Also according to [6,7], generation costs of new onshore wind plants are beginning to undercut costs of coal energy plants with wind at 5 ¢/kWh, again confirmed by the global auction values of about 5 ¢/kWh for onshore wind [8].

Offshore wind. Furthermore from [6,7], offshore wind requires 11.5 ¢/kWh for profitability. Global auction values currently amount to 13-14 ¢/kWh [8].

Bioenergy for electricity. Forestry products from the USA have extensively been used in energy plants of Great Britain. Apparently, this business has been profitable. The subsidy was e.g. 4.2 p/kWh in 2018-2019 (delivered average electricity 35.7 TWh/year [10] in 2018-2019, with subsidy of 1.5 Bio. £/year [11]). – Global average levelized costs of electricity production from newly commissioned biomass plants are now at 7 ¢/kWh [7,12].

Bioenergy for heating. In developing countries, wood as energy source exhibits significant cost competitiveness as compared to oil and also coal [13] with the added benefit to generally contribute to local income from regional wood collection. – Also in developing countries, natural reforestation can suffice funding of 20 \$/ha [14]. – In an experience study covering a variety of European countries and biomass sources, the heat supply costs of 20-200 kW systems have been determined in the order of 4-9 c€/kWh [2].

Conclusion

From project experience, energy production from PV, onshore wind, and biomass has generally become competitive with fossil-fuel based energy supply. This applies (i) to electricity production on global average (marginal-cost operating fossil fuel plants disregarded), (ii) to heat supply in a significant part of the world.

4.2 Overall transition costs from projection studies

So far, the present description has been focused on the energy sector. In this section, the view is widened to the overall transition venture from fossil sources to renewables by looking at projection studies. Again, the aim is to extract essential insight as base for a broader consensus in society on subjects such as capital need and CO₂ pricing.

Study 1. According to an analysis for Austria [15], a CO₂ price of 20-50 €/kWh gives suitable stimulus for development of the bioenergy market; the price is to be subjected to regular revisiting and in case, amendment according to actual evolvments, expected to approach zero within 20-40 years.

Study 2. In an analysis for the USA [16], the CO₂ emissions abatement potentials are examined for the present decade in dependence on various CO₂ price levels in the range 0-83 \$/CO₂, subdividing the entire energy consumption into the utilization sectors electricity, industry, buildings, and transportation. The only significant abatement sensitivity to the CO₂ price is revealed for the electricity sector. From year 2020 to 2030, the CO₂ savings are projected as 23, 61, and 67% for CO₂ prices in the ranges 14-24, 50-60, and 73-83 \$/tCO₂, respectively. These figures reveal that the abatement leverage is markedly decreasing when raising the CO₂ price beyond 50 \$/tCO₂. Furthermore it is predicted for 2030 that 83% of the CO₂ emissions abatement potential is associated with the electricity sector while 9, 5, and 3% are expected from the sectors industry, buildings, and transportation, respectively.

Study 3. The global analysis of [17] projecting from 2000 to 2030 shows the possibility of long-term (year 2100) atmospheric CO₂ concentration stabilization at 450-550 ppmv with CO₂ emissions abatement ratios between 2 and 32% relative to baseline (emissions reduction with versus without abatement measures). To first order, the relationship between abatement ratio and CO₂ price is shown linear, the abatement ratios 2-32% relating to CO₂ prices of 0-50 \$/tCO₂. CO₂ prices below 30 \$/tCO₂ are expected to bear negligible impact on world gross (domestic) product. From the linear relationship, 30 \$/tCO₂ correspond to an abatement ratio of 20%.

Study 4. The global analysis of [18] projecting from 2010 to 2030 indicates a global carbon emissions reduction potential of about 10 GtC/year at approximately neutral costs, which means virtually zeroing present emissions at net zero cost. Subsequently, two aspects of the study are regarded in more detail.

(i) For the electricity production sector in year 20 of abatement implementation, the study prognoses abatement costs of 146 Bio. €/year. The study relates this to a forecast electricity production of 36,000 TWh/year. This means an abatement surcharge of 0.5 ¢/kWh (1.2 \$/€). Here, the following amendment is proposed. The transition to renewables is seen cost-competitive already at present (see before, § 3 and particularly § 4.1) and even more for the future from continuing learning curves. To first order, renewables have zero carbon emissions. Thus in the electricity sector, the emissions abatement from the transition to renewables comes cost-neutral.

(ii) For afforestation & reforestation, [18] apparently consider costs of about 100 \$/ha/year. In reality as mentioned earlier (§ 4.1), investment need for afforestation can be as low as 20 \$/ha. However when considering expansion at large scale, average costs may need be calculated higher. To explore an upper boundary, costs for land, plantation, and maintenance may each amount to 100 \$/ha/year. With these values, planting the 350 Mha of new forests in course of the Bonn Challenge / UN New York Declaration during 20 years comes within overall cost neutrality when allowing for the amendment (i) before. This

still applies if 5% of electricity production remains from fossil sources and the related CO₂ emissions are rather costly sequestered by CCS (Carbon Capture and Storage; details not presented).

Conclusion

From a (highly selective) analysis of previous studies on the one hand, an upper limit for the renewables transition stimulus is inferred with 50 \$/tCO₂ per abated CO₂ emissions. On the other hand, it appears likely that about 90% of current CO₂ emissions can be cut in overall cost-neutral manner.

4.3 CO₂ abatement stimulation from CO₂ pricing

Nevertheless even with transition cost neutrality, society may thrive for ascertained or accelerated transition pace calling for expansion of the existing regulatory measures. A frequently discussed means is CO₂ pricing, as addressed earlier (§§ 2.3, 3) and revisited here in more general terms. The principal idea appears straightforward: fossil sources become levied so that the free-market forces lead to the alternatives. However, it seems non-obvious how the plain application of a CO₂ price addresses (i) the already existing competitiveness of the new techniques and (ii), the heterogeneity between the abatement means, i.e. some with costs, others with benefits, all bottom line economically balanced.

A plain CO₂ taxation has the potential to first raise prices in general, the intended directing effect coming secondary. It poses first a multi-burden on every household from a variety of channels such as electricity, heating, transportation, and consumer goods. As result, e.g. a CO₂ tax of 50 \$/tCO₂ means average expenditure increase of 760 and 320 \$/year for every person in the US and EU, respectively [19].

Conclusion

If further regulation by CO₂ pricing is perceived required in addition to the existing means, noticeable differentiating is requested as opposed to plain CO₂ pricing to keep the burden on the households at appropriate levels (see § 3 for a differentiating example).

4.4 CO₂ abatement stimulation from carbon certification/crediting

As further transition stimulus means, the carbon certification/crediting mechanisms has been in use. A detailed discussion of benefits and deficiencies lies outside the present scope. The basic idea is to attract private capital for the financing of carbon abatement measures. Principally on the one hand, the certification/crediting mechanism exhibits aspired differentiative and distributive characteristics. On the other hand, it is judged highly nontransparent, costly (assessments, agencies), potentially ineffective regarding real emissions reduction, and questionable if bearing the required differentiating specificity (see examples in [4]). As alternative means for instance, replacement of incandescent lamps and change of agricultural practices may be pursued by prohibition and energy efficiency in buildings facilitated by credit supply.

Conclusion

In case reinforced transition stimulus is aspired, dedicated legislation may be advantageous over free-market mechanisms such as carbon certification/crediting. It is emphasized that legislation is inherently present in any case, thus the question is about the prescriptive extent in the various stimulus mechanisms.

4.5 Discounting costs and benefits between present and future

Discounting of costs and benefits in tail of climate change and its mitigation has been a highly disputed topic. The following pragmatic view is proposed from the present studies.

Viewing the past climates through tens and hundreds of million years, the dependence of near-surface temperature on the atmospheric CO₂ concentration is well known for equilibrium climate states [20]. At present, the climate is in a transient state on its way to a future new equilibrium. If the CO₂ concentration remains steady at some point, the new equilibrium temperature is asymptotically approached on millennium time scale (cf. [21]). Relative to this time scale, the CO₂ concentration increase of the industrial era is young and thus, nature's asymptotic proceeding still at its onset, with (i) relatively strong CO₂ uptake from the atmosphere, i.e. 3%/year [5]; (ii) relatively unchanged ice sheets, indicated by the sea level (see below); (iii) temperature following the CO₂ concentration increase according to a simple prescription and approximately linearly [21]; (iv) with still no recognizable legacy contribution from the move towards the future equilibrium climate state (conclusion from (i-iii) and overall comprehension).

It is hypothesized that the natural processes will remain the same from the industrial-age past into the medium-term future (in the order of ≥ 100 years). Therefore in case the emissions will continuously be reduced within this time frame, nature will take the reverse path as in the past when emissions were rising. This leads to the following inference for (i) sea level and (ii) atmospheric CO₂ concentration with entailed temperature.

(i) During the past about 450,000 years, the sea level has changed with surface temperature by roughly 20 m per 1°C temperature change [22,23]. In the recent past during the industrial eon, temperature has risen by about 1°C. From this, a sea level rise of 20 m is to be anticipated, of which about 1% has been experienced until the present. This is interpreted that the sea level has rather slowly followed temperature change. From the preceding reversibility hypothesis, a realistic probability is expected that sea level remains rather unchanged if the recent temperature increase is reversed at about the same pace.

(ii) For the anthropogenic carbon emissions, the reversibility hypothesis expects that the 3%/year CO₂ uptake of the past (for the 'extra' atmospheric CO₂ additional to equilibrium quantity) [5] remains for the future. For instance if emissions become reduced by 3%/year (year-on-year, geometric), the atmospheric CO₂ concentration is projected to top at 450 ppmv in year 2035 and to return to 335 ppmv in 100 years

from now, with then emissions at 5% of present levels. If the CO₂ concentration would remain constant afterwards (at 335 ppmv), the associated equilibrium temperature (long-term, ≥ 1000 years) is anticipated at 1.5°C above pre-industrial levels (cf. [20,21]). This temperature confinement, in turn, permits the assumption that none of the previously discussed tipping points be reached (elaboration outside the present scope).

An emissions reduction of 3%/year (geometric) seems feasible as reasoned by the following thoughts. (1) It means e.g. 240 MtC/year less emissions in year 2021 than in 2020. This compares well with the given abatement potentials. For instance according to [4], emissions of 285 MtC/year can be reduced year-on-year by prudent use of land if the measures are (linearly) implemented over 20 years [4]. (2) If existing carbon emitting equipment has depreciation times of 20 years and is being replaced at their end, the replacement rate is (linear) 5%/year to first order. (3) The potential cost neutrality (§ 4.2) indicates investment volumes and rates of the same order as in the past and implies the reduction being paid by the consumers within overall unchanged prices. (4) The required societal preparedness is presumed attained by now.

Jointly regarding all preceding aspects, special discounting of efforts and achievements between the present and the future appears unnecessary. Furthermore when pursuing an emissions reduction of 3%/year year-on-year, the burden in absolute terms is largest for the present generation and steadily decreasing into the future. This may level potential generational injustice. Yet dependent on the long-term temperature increase (e.g. 1.5°C above pre-industrial far beyond year 2120), the persisting impacts (e.g. the related sea level rise by 30 m) need be appropriately envisaged by society.

Conclusion

With – judged feasible – effort of a year-on-year (geometric) emissions reduction of 3%/year, the atmospheric CO₂ concentration is projected to 335 ppmv by 2120. If the concentration stayed constant afterwards, the final equilibrium temperature increase since pre-industrial times is estimated to 1.5°C, which will asymptotically be approached on millennium time scale. The costs for the emissions reduction have the potential of approximate cost neutrality, with investments in the same order as usual regarding volumes and rate. Before this background, special discounting appears unnecessary. Yet, significant sea level rise is to be prepared for on the long term.

5. Discussion

A central aim of the present studies is to bridge between the sophisticated scientific research and the broader society. Societal consensus finding needs be based on a concentrate of all available information. Therefore, a central task is to identify the essentials by the driving terms and to crystalize the simple-most description, yet thriving for comprehensiveness and fact-based objectivity and transparency. The present article focuses on the costs of the transition from fossil fuels to renewables and the required economic

transmission means. Since searching for the driving terms, the work focuses on carbon, i.e. CO₂ emissions.

A practicable, at the same time highly comprehensive and fully documented framework is presented to transparently estimate energy generation costs for the various primary energy sources. This scheme is applied in exemplary manner, the input values perceived representative for (largely) global averages. Since concentrating on the driving terms, extensive literature review and statistical analysis are beyond the present scope. Generally, the estimate results are in good agreement with existing literature (details not presented). The present estimates are then compared with field reports and projection studies. Finally, the characteristics of CO₂ pricing and carbon certification/crediting are examined as potential transmission belts for the transition from fossil sources to renewables. The major results are as follows.

Regarding energy supply to first order, renewables are proposed to be considered competitive to fossil sources – resulting from field reports, conducted auctions, and the present levelized cost estimation. Significant exceptions are electricity production from marginal-cost generators (with extraordinarily low production costs) and offshore wind (posing the high-cost boundary). Regarding the overall transition to the low-carbon future, the abatement is inferred to potentially come cost-neutral with familiar investment volumes and rates.

Much of the previous scientific research has been related to the possible response of nature on unaltered human action. The results are judged to have revealed that fainceance be no choice. Here from observations of nature, a reduction of anthropogenic carbon (CO₂) emissions by 3%/year (year-on-year) for 100 years is inferred to bring the CO₂ concentration back to the 1970-level by 2120 and to confine the associated long-term (≥ 1000 years) temperature contribution to 1.5°C. Such reduction probably avoids the feared natural tipping points (details not discussed). The 3%/year-reduction certainly is ambitious as for instance, it means a reduction of 26% in 10 years. On the other hand, it appears feasible from the fulfillment of crucial prerequisites such as technical readiness, economic soundness (consistency of costs, investments, discounting), and societal preparedness.

The opinion may be that transition stimulus is required in addition to the already existing means of taxation, subsidy, carbon certification/crediting, and CO₂ pricing. The present studies have devoted a deeper look to (enhanced) CO₂ pricing as the preferred transmission belt. In electricity production, the plain application of a CO₂ price retains imbalances given by the heterogenous cost characteristics (e.g. onshore wind with about half the levelized costs as offshore wind and biomass). Beginning at 30 \$/tCO₂, overall economy may start to noticeably deteriorate. Above 50 \$/tCO₂, transmission effectiveness may markedly decline. For instance with plain 50 \$/tCO₂, the burden on every household is viewed grave to prohibitive, depending on regional specifics. As exemplarily shown, this can be rendered proportionate by redistributing levy to subsidy.

In addition, the overall transition cost neutrality calls for a distributive scheme. While some abatement measures come with economic benefits (e.g. in the buildings sector), others come with costs (e.g. in

forestry). The plain application of a CO₂ price primarily raises general price levels and only secondarily, facilitates the aspired transition towards renewables. The quest is inferred to weigh alternative transmissions belts against CO₂ pricing and also carbon certification/crediting, particularly by exploiting the legislative possibilities. The required differentiation and commensurability may best be attained by detailed regulation, continuously reviewed and amended according to actual evolvement.

Declarations

Supplementary Materials: All data and code are available: [Simplified climate modelling](#).

Conflicts of Interest: No conflict of interest is to be declared.

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Figures

Figure 1

Levelized energy production costs for electricity and heat supply from the present levelized estimation scheme with combined carbon levy & subsidy at 50 \$/tCO₂ for various primary energy sources: coal, natural gas (NG), oil, wind onshore and offshore, photovoltaic (PV), biomass. Dashed rectangle and line to guide the eye regarding competitiveness of the various production techniques. NG low, medium, peak price: three price levels; PV without and with profit; biomass in CHP mode and direct combustion. Further details see text.

Supplementary Files

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