30th NENE 2021
September 6 - 9
BLED-SLOVENIA
International Conference Nuclear Energy for New Europe

CO2 Mitigation Using Atomic Power-2025 Deployment

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ABSTRACT

World energy is expected to continue increasing 2.25%/a through 2100, requiring ~40 terawatts-electric average generation by 2105, equivalent to 120 terawatts-thermal. Sufficient utility-scale energy storage to average 40 terawatts wind and solar energy, ~2 terawatt-a, costing ~2000 trillion USD at 0.10 USD/Wh, will never exist. Wind and solar energy collection cost for ~500 TWe nameplate will add another ~1500 trillion USD, not counting ~500 trillion USD transmission cost. Absent utility-scale energy storage, wind, solar and big hydro will never average more than 3 terawatts electric generation. CO2 mitigation requires atomic power expansion 5%/a starting 2025 to 50 TWe nameplate. Otherwise fossil fuel depletion achieves ~1300 ppm CO2 by 2100. Atomic power can be any combination of: (1) seawater-uranium-fuelled LWR, (2) FBR, or (3) CANDU D2O slow-neutron pile. Sufficient D2O will be available from electrolysis and fuel-cell hydrogen consumption. Atmospheric CO2 modelling assumes ocean continues absorbing 1/3 of industrial CO2 emissions. Fossil fuel is modelled as gasoline, C8H18. Maximum CO2 is ~850 ppm around 2110. After fossil fuel is phased out, CO2/CH4 (GHG) atmospheric half-life is estimated 83 a, resulting in 350 ppm CO2 around 2350. Results presented in this work are a modification of 2016 Korean prize-winning paper that used now-obsolete 2020 atomic power deployment.

1 INTRODUCTION

This is the Tenth paper in a series [01][02][03][04][05][06][07][08][09]. Nearly two decades have passed since ICAPP02 paper analysing CO2 mitigation using atomic power [01]. Starting year-2000 atomic power deployment at 5% per year gave year-2080 maximum to be 635 ppm-CO2 [07]. Starting year 2020 atomic power deployment at 5% per year gave year-2100 maximum CO2 to be ~700 ppm-CO2 [09]. Starting 2025 atomic power deployment at 5% per year gives 2110 maximum CO2 to be ~850 ppm-CO2. Each year wasted increases CO2 maximum ~30 ppm-CO2. Initially, each GW atomic power delays CO2 doubling one week [01].

2 BACKGROUND

World energy and CO2 have both been increasing 2.25%/a since 1800, despite ~4 trillion USD spent on "renewable energy," mostly windmills and solar PV. Between year-2000 and year-2100, World energy consumption will grow from 5 TWe to 40 TWe equivalent (~50 TWe dispatchable nameplate) base-load generation.

10 TWe continuous power is required to pump 17,500 km^3/a fresh water south from Russia and Canada to avoid ~4 cm/a sea level rise from ground water pumping. Water volume is from applying California's 100 km^3/a water use for 40 million to 7 billion.

Pumping energy assumed same as for seawater desalination, 4000 watt-hour per m^3, and 80% overall equipment efficiency.

Refrigeration [10] at least +0.04/a (+4% per year) starting 1800 at 80 MW electric equivalent (ice storage: 0.0075 EJt/a). 4%/a extrapolation to 2100 results in 13 TWe. "(i) Current energy projections do not consider a Cooling for All scenario and therefore either we meet the UN SDG [Sustainable Development Goals] or the [2015] Paris Climate Targets but not both [10]." Absent utility-scale energy storage, wind and solar energy can never usefully provide more than 1/6 of all kWhe [11]. Year-2020 windmill and solar PV nameplate deployment is not keeping up with average equivalent world energy consumption increase, much less adjusted for ~20% utilization.

3 DESIGN INPUT

3.1 Year 1800 World Energy Consumption Estimated 13 EJt/a

900E+06 persons * 800 W/m^2 * 0.01 efficiency * 0.30 fraction use * 6 h/d
* 0.25 a/a growing season * 365.25 h/a * 3600 s/a * 10,000 m^2/hectare
* 0.25 hectares/person = 10.7 E+18 J/a ~ 13 EJt/a. (01)

3.2 Fossil Fuel Model

World average fuel N-octane C8H18 Liquid 114.22852 kg/kgmole, Carbon emissions:

1.0 EJt HHV C8H18 = 1 EJt HHV C8H18 * (1.0 E+12 M/E)/5471.55 MJ/kgmole-C8H18 *(8 C/C8H18) * 12 kg-C/kgmole-C * 280 ppm/610.0 E+12 kg-C = 0.0080536 ppm-C. (02)

3.3 280 ppm Preindustrial Atmospheric CO2 Carbon Mass

509.4 Tm^2 * 101325 N/m^2/9.80665 m/s^2 * 12/29 * 0.000280 = 610 Tkg-C. (03)

4 ASSUMPTIONS

Energy conversion comparison basis: LHV. Energy and CO2 emission basis: HHV.

4.1 Atmospheric CO2 Modelling Absent CO2 Mitigation:

ppmCO2 = 280 ppm Preindustrial + Exp(0.0225/a * (a - 1800)). (04)

Peak CO2 concentration is 1330 ppm if Uoo fossil fuel is consumed. World Uoo (ultimate resource) fossil fuel assumed 8 times 430 Tkg USA coal reserves and 2/3 CO2 emissions assumed remains in atmosphere. This will occur year-2109 according to Equation (04). Reducing a by 2 after 2019 allows for the 2008 recession and COVID-19 to give 419.6 ppmCO2 July 01, 2021 (2021.5) versus Mauna Loa: 419 ppmCO2.

4.2 Seawater CO2 Absorption

Seawater CO2 Absorption has been previously modelled to be ~1/3 of CO2 emissions [12]. This condition is presumed to exist into the indefinite future and presently exists [13]:

Fossil Emissions = Air accumulation + Seawater absorption
= Air accumulation + 1/3 Fossil Emissions. (05)

35.3 Tkg-C net forest CO_2 emission is expected if world temperature increases 2 Centigrade [14]. Net forest emission is neglected because it is ~1/32 of (3/2) * 610 Tkg-C fossil emissions corresponding to CO_2 doubling. Rearranging Equation (05) gives:

$$\text{Air Accumulation} = (2/3)\ \text{Fossil Emissions} = 2 * \text{Seawater Absorption}. \quad (06)$$

4.3 World Thermal Equivalent Energy since 1800, HHV basis:

Richard Rhodes, Energy; Unconquered Steam! "The year 1800, the turn of a new century, hinged in Britain between the old organic economy and the new economy of industry powered by fossil fuel." Modern civilization begins 1800: Alessandro Volta makes first electric pile (battery). James Watt's 1769 steam engine condenser patent expires.

$$\text{World Energy} = 8.5\ \text{EJt/a} + 4.5\ \text{EJt/a} * \text{Exp}(0.0225/\text{a} * (\text{a} - 1800)). \quad (07)$$

$$\text{Biofuel energy} = 13\ \text{EJt/a} * \text{Exp}(0.007/\text{a} * (\text{a} - 1800)). \quad (08)$$

$$\text{Zero carbon energy} = 0.00040\ \text{EJe/a} * 3\ \text{Jt/Je} * \text{Exp}(0.05/\text{a} * (\text{a} - 1800)). \quad (09)$$

Equations (02), (06), (07), (08) and (09), are used to model atmospheric CO_2 accumulation after (09) is modified using 0.00030 EJt/a instead of 0.00040 EJt/a to adjust for 2025 start instead of 2020 start. These equations roughly follow British Petroleum results [15][16], given the somewhat arbitrary value of toe heat content.

4.4 Atmospheric CO_2 After Fossil Emissions Cease

Atmospheric model changes after fossil fuel emissions cease. Using Equation (06) and first derivative of (04) gives seawater CO_2 absorption rate:

$$\text{Seawater Absorption} = (1/2) * 0.0225/\text{a} * \text{Exp}(0.0225/\text{a} * (\text{a} - 1800)$$
$$= 0.0225/\text{a} * \text{Exp}(0.0225/\text{a} * (\text{a} - 1800 - (\text{Ln}(2)/0.0225)). \quad (10)$$

If Seawater absorption is assumed proportional to concentration above 280 ppm, then comparing Equation (10) to Equation (04) means:

$$\text{Seawater absorption} = 0.0225/\text{a} * \text{Exp}(0.0225 * (\text{a} - (\ln(2)/0.0225) - 1800)), \quad (11)$$

modelling seawater absorption as proportional to excess CO_2 from (ln(2)/0.0225) years earlier. Implication is that during atmospheric CO_2 increase, seawater CO_2 absorption results in an 30.8 year atmospheric CO_2 half-life.

A separate CO_2 decay model exists [17] with a CO_2 decay constant is inverse of 120 a, the 1/e duration. CO_2 half-life is 120 a * ln(2), equal to 83 a. Switching models at CO_2 peak gives the year returning to 350 ppm CO_2:

$$\text{Peak Year} + \ln[(\text{Peak CO2} - 280\ \text{ppm})/(350\ \text{ppm} - 280\ \text{ppm})]/(120\ \text{a})$$
$$= \text{year back to 350 ppm}. \quad (12)$$

Figure 1 shows the 83 a half-life CO_2 decay model switch arbitrarily applied after 2120. Near Peak atmospheric CO_2 concentration zero carbon energy exceeds total energy, creating a "negative CO_2" phenomenon.

4.5 Carbon Emissions versus GDP, assuming ocean absorbs 1/3 of CO2

2020 CO2 emissions = ~ (3/2) * 3.176 ppm/a * 610,000 Mt/280 ppm preindustrial
= 10379 Mt/a = 10.379 trillion kg-C/a. (13)

2020 world nominal GDP ~ 95 trillion USD: Each USD world economic activity emits 0.1 kg-C. This is equivalent to 10,000 USD per tonne carbon versus Chinese carbon trading price of ~6 USD per tonne carbon.

5 RESULTS

Combining Equations (06), (07), (08) and (09) using C8H18 for reference fossil fuel Equation (02), 0.0004 for 2020 start and integrating from year-1800:

ppm-C = (2/3) * 0.0080536 * [(4.5/0.0225) * {Exp(0.0225 * (t - 1800)) - 1.0}
+ 8.5 * (t - 1800) - (13/0.007) * {Exp(0.007 * (t - 1800)) - 1.0} - (0.0004 * 3/0.05)
* {Exp(0.05 * (t - 1800)) - 1.0}] + 280 ppm-C preindustrial. (14)

Integration starts year-1800 with 280 ppm-C atmospheric carbon. Figure 1 shows results from Equations (04), (07), (08), (09) and (14). Figure 1 shows several CO2 Scenarios. To allow for 2025 start, instead of 2025 start, Equations (09) and (14) 0.0004 coefficient is changed to 0.0003. This is because Exp(-0.05/a * 5 a) is approximately 3/4, also neglecting lower integration limit, to account for 5 year delay from 2020 to 2025. This also causes Equations (07), (08), and (09) to give results roughly corresponding to [18] 2017 page 33 (World energy source fractions). For 2025 start, Equation (14) gives 843 ppm peak in year 2110. Using these numbers in Equation (12), return to 350 ppm CO2 occurs 2360.

6 CONCLUSION

Only atomic power can mitigate atmospheric CO2 and simultaneously expand world energy by a factor of 10. Atomic power can be any combination of LWR [03], FBR [04][05][06] and D2O-moderated [07] piles. 4000 Mt seawater uranium [03] can average 40 TWe for ~23,000 a in FBRs or 450 a in once-through LWRs [Year 2016: 2500 TWhe required 0.063 MtU] [19]. Uranium [~100 ppm in phosphate rock] extracted from 200 Mt/a phosphate ore 0-54-0 fertilizer production can produce 20 TWe. After ~1000 years FBR fission-product curies falls below uranium curies consumed. Atomic power consumes radioactive waste. CO2 will max out at ~3 times preindustrial 2110, perhaps only because fossil fuel reserves will be depleted. UN 11 billion 2100 population and a world South Korean per capita income gives 2100 world GDP 6 times that of 2020. After 4 decades, energy to GDP ratio may revert to unity [20]. Overly optimistic energy assumptions may have consequences [20].

World energy increase 6 times 2020 consumption requires ~40 terawatts-electric average power generation by 2100, equivalent to 120 terawatts-thermal energy. Sufficient utility-scale energy storage to average 40 terawatts wind and solar energy, ~2 terawatt-a, costing ~1000 trillion USD at 0.05 USD/kWh, will never exist. With the exception of NH3-H2O storage [21][22] and lithium batteries, nothing changed on the energy storage front in nearly four decades [23]. Wind and solar energy collection cost for ~500 terawatt nameplate will add another ~1500 trillion USD, not counting transmission. World hydroelectric power maximum potential is 1.6 terawatts average [24]. Minus utility-scale energy storage, wind, solar and big hydro will never usefully average more than 3 terawatts electric generation, twice hydroelectric potential, a negligible contribution. Mitigating CO2 requires dispatchable zero-carbon generation that grows 5%/a from 2025. Atomic power, is the only viable ~50 terawatt nameplate, dispatchable, zero-carbon electric source. Atomic power must expand 5%/a from 2025, either to mitigate CO_2 or replace depleted fossil fuel. Atomic power can be any combination of: (1) seawater-fuelled LWR, (2) FBR, or (3) D_2O slow-neutron pile. Sufficient D_2O will be available from electrolysis and fuel-cell hydrogen consumption. Half world energy in 2120 could come from phosphate fertilizer by-product uranium at 50% thermal efficiency, assuming phosphate rock is 100 ppm uranium.

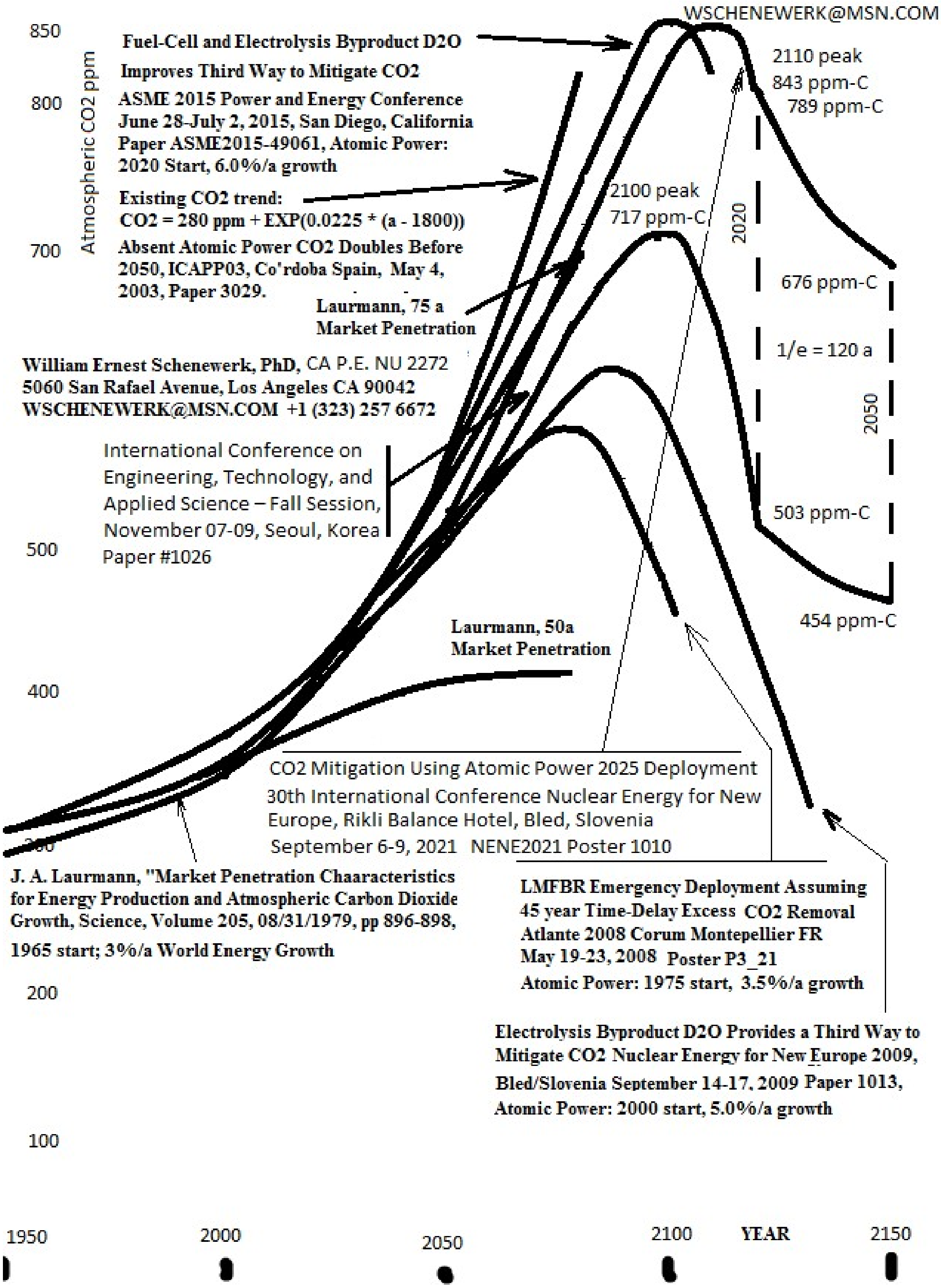

Figure 1: CO2 Mitigation Using Atomic Power, 2025 Start

NOMENCLATURE

a annus = year = 8766 h
bbl Barrel of oil, 42 gallons, 42 * 231 * 0.0254^3 m^3/ 08202020: -37.6 USD/bbl
Btu British Thermal Unit = 1054.3503 Jt = 1 lb-H2O * (61 F - 60 F), SI calorie
BOE Barrel of Oil Equivalent, USA IRS = 5.8 MMBtu HHV ~ 6.1 GJt HHV ~ 5.4 GJt
C8H18 Gasoline: 5.075 GJ-LHV/kg-mole; 5.47155 GJ-HHV/kg-mole
CCGT Combined-Cycle Gas Turbine, LM 100 + ST eta = 0.55, air condenser
CT Combustion Turbine
E Ecto = 10^18
eta [Greek symbol] power plant efficiency = net kWhe/LHV kWht
FBR Fast (neutron) Breeder Reactor (pile)
HHV Fuel Higher Heating Value, exhaust H2O condensed
k kilo = 10^3
Je Electrical joule, subscript = mechanical or electrical energy, equivalent to ~3 Jt
Jt thermal joule, Subscript = thermal energy, 3 Jt ~ 1 Je in conversion equipment
kWh 3414.4250 Btu SI Basis; 3412.142 Btu NIST Cal/g basis
LHV fuel Lower Heating Value, exhaust H2O leaves as steam
LWR Light (slow neutron) Water-Moderated Reactor (pile)
M Mega = 1.0E+06 (MM = Roman million)
R NIST 2018 CODATA Gas Constant 8.314462618... J/g-mole-K = n * k
SCF standard cubic foot at 30"Hg and 60 F ~ 60/50000 kg-mole
T Tera = 10^12
toe metric tonne oil equivalent = 42 GJt = 7.33 barrels oil
TW-a terawatt-year electrical energy storage = 31.5576 EJ
t tonne = 1000 kg, except as subscript means thermal energy

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