Appendix A

Crib Sheet — Summary of Facts

We may use slightly different sources and numbers in this crib sheet than those we have used in the book. The numbers are reasonably consistent, yet convey typical estimation differences that show up when different sources or years are used.

Unless otherwise noted, the principal data source is US EIA International Energy Outlook, Oct 2021.

Please bring any errors to our attention asap.

Chapter 1: Population

See Fig 3: Population (in billion)					
	1960	2020	2100e	Δ	%Δ
OECD	815	1,369 ∼	1,400	+31	2%
USA	187	331 ↗	434	+103	31%
EU27	356	445 ↘	364	–81	–18%
not OECD	2,220	6,426 ↑	9,475	+3,049	47%
Asia	1,705	4,641 ∼	4,720	+79	2%
China	660	1,439 ↓	1,065	–374	–26%
Othr Fr East	963	2,206 ↘	1,826	–380	–17%
South Asia	517	1,605 ∼	1,689	+84	5%
India	451	1,380 ∼	1,447	+67	5%
Africa	203	1,341 ↑↑	4,280	+2,939	219%
Sub-Sahara	220	1,094 ↑↑	3,776	+2,682	245%
Nigeria	45	206 ↑↑	733	+527	256%
World Total	3,035	7,795 ↑↑	10,875	+3,080	40%

Primary Data Source: Worldbank and United Nations.

Chapter 2: Primary Energy (PE)

See Fig 9 and 8: PE By Region (ca 2022)			
	Popln	Total	pPpD
OECD	1.38	71 PWh	141 KWh
USA	0.33	28 PWh	232 KWh
Europe	0.60	24 PWh	109 KWh
Not OECD	6.50	116 PWh	49 KWh
China	1.45	48 PWh	90 KWh
India	1.41	12 PWh	23 KWh
Other Asia	1.18	14 PWh	32 KWh
Africa	1.37	7 PWh	14 KWh
Sub-Sahara	1.04	2 PWh	5 KWh
USSR (CIS)	0.25	11 PWh	121 KWh
Mid-East	0.26	10 PWh	111 KWh
Latin America	0.52	8 PWh	41 KWh
World	7.88	187 PWh	65 KWh

Primary data source is US EIA. Population is in billions. pPpD is *per Person per Day*. USSR, Mid-East and Latin America are from British Petroleum (BP).

See Tbl 5: Energy Purpose

	USA	World
Home/Work	40%	30%
Transport	30%	20%
Industry	30%	50%

Primary Source: NAS.

See Tbl 10: Primary Energy Growth

1965	2019	2050e
49 PWh	185 PWh	260 PWh

The 1965 estimate is inferred from Our World in Data and the EIA 2019 number.

See Tbl 10: Primary Energy Use Growth

	2022	2050e	Δ	
OECD	71	82	+11	PWh
USA	28	32	+3	PWh
EU	24	28	+4	PWh
Non-OECD	116	177	+62	PWh
China	48	58	+10	PWh
India	12	35	+23	PWh
Other Asia	14	25	+11	PWh
Africa	7	13	+6	PWh
World	187	260	+73	PWh

Over the next 30 years, the world is expected to increase its energy consumption by about 40%.

See Pg 31: Data Disagreements

BP	EIA[1] HDB	EIA[2] IEO
162 PWh	186 PWh	173 PWh

All three estimates are for total primary energy consumption for the world in 2019. Our World in Data also uses the BP data. The first EIA number is from the Historical Data Browser, the second is from the International Energy Outlook.

See Fig 11: Energy Sources (2019)

Biomass	11 PWh	7%
Coal	44 PWh	28%
Oil	54 PWh	34%
Natgas	39 PWh	25%
Nuclear	7 PWh	4%
Hydro	10 PWh	6%
Wind	4 PWh	3%
Solar	2 PWh	1%
Total	173 PWh	100%

Non-fossil fuels are grossed up as if they had similar efficiency losses as fossil-fuels.

Chapter 3: Emissions

See Fig 1: CO_2 Equiv, By GHG

CO_2	38 $GtCO_2$	86%
Methane	9 $GtCO_2e$	20%
NOx,CFC,+	5 $GtCO_2e$	11%
Land Charge	4 $GtCO_2e$	9%
Total	55 $GtCO_2e$	100%

See Fig 3: By Emitting Use

Energy	37 $GtCO_2e$	73%
Agriculture	10 $GtCO_2e$	20%*
Other	4 $GtCO_2e$	8%

If the land charge accrues to agriculture, then agriculture's share increases from 20% to 25%.

§3.2: Annual Atmosphere Change:

- Human Emissions: +38 $GtCO_2$.
- First-Year Natural Atmospheric CO_2 Removal: ≈20 $GtCO_2$.
  (Total removal: 100s-1000s of years.)
- Extra Human-Caused Atmospheric:
  +18 $GtCO_2$/year ≈ +2.5 ppm/year. (Relating Emissions in $GtCO_2$ to PPM.)
- 1870: 2,200 $GtCO_2$ ≈ 280ppm.
- 2021: 3,200 $GtCO_2$ ≈ 420ppm.

See Tbl 14: CO_2 Emissions, 2022→2050e

	2022	2050e	Δ	
OECD	12.1	12.1	–0.0	$GtCO_2$
USA	4.8	4.8	–0.0	$GtCO_2$
EU	3.8	3.7	–0.1	$GtCO_2$
Non-OECD	24.2	30.8	+6.6	$GtCO_2$
China	11.0	10.5	–0.5	$GtCO_2$
India	2.7	5.8	+3.1	$GtCO_2$
Other Asia	2.8	4.9	+2.0	$GtCO_2$
Africa	1.3	2.0	+0.7	$GtCO_2$
World	36.8	42.8	+6.6	$GtCO_2$

The table in the text quotes log-growths. The table here shows $GtCO_2$ instead.

See Tbl 17: CO_2 Emissions (ca 2022)

	Total	pPpY
OECD	12.1 $GtCO_2$	8.8 tCO_2
USA	4.8 $GtCO_2$	14.4 tCO_2
Europe	3.8 $GtCO_2$	6.4 tCO_2
Not OECD	24.2 $GtCO_2$	3.7 tCO_2
China	11.0 $GtCO_2$	7.6 tCO_2
India	2.7 $GtCO_2$	1.9 tCO_2
Other Asia	2.8 $GtCO_2$	2.4 tCO_2
Africa	1.3 $GtCO_2$	1.0 tCO_2
Sub-Sahara	0.4 $GtCO_2$	0.6 tCO_2
World	36.3 $GtCO_2$	4.6 tCO_2

Fossil-fuel based CO_2 emissions. pPpY = per Person per Year.

Chapter 4 and 5: Temperature

§4.4.4. Atmosphere State:

- Long-Run: $2\times CO_2$ (ppm) ⇒ +1.0°C. Includes water vapor.
- ⇒ 50% increase from 280-420 ppm (+50%): ≈ 0.5°C.

See Fig 5 and 9: Estimated Planetary Conditions

	Year	CO_2 in ppm	Temp in °C	SeaLvl in m
	–100,000	236	–2.1	
Vostok	–30,000	206	–6.8	–80
Vostok	–20,000	200	–8.1	–133
	–10,000	240	–2.5	–62
	0	280	–0.4	–0.1
	1400	280	–0.3	0.0
Mann	1700	276	–0.8	0.0
Mann	1800	281	–0.5	0.0
	1980	339	**0.0**	**0.0**
NASA	2000	370	+0.3	+0.2
NASA	2020	415	+1.0	+0.2
NASA and IPCC 2021 Report, Page SPM-29				
RCP 4.5	2050e	500	+1.5	+0.3
	2100e	560	+2.5	+0.3
RCP 6.0	2050e	500	+1.6	+0.3
	2100e	720	+3.0	+0.4
RCP 7.0	2050e	600$^{(?)}$	+1.7	+0.3
	2100e	850$^{(?)}$	+3.6	+0.5
Clark	10,000e	630	+3.0	+37

The base year is 1980. Clark et al's estimate is based on RCP 6.0 extrapolated.

Data Basis: mostly IPCC 2021 6th Report for RCP 4.5 and 7.0. RCP 6.0 is now interpolated. Sometimes IPCC 5th.

See Fig 5.1: RCP Emissions

	2050e	2100e
RCP 4.5	45 $GtCO_2$	15 $GtCO_2$
RCP 6.0	55 $GtCO_2$	50 $GtCO_2$
RCP 7.0	60 $GtCO_2$	80 $GtCO_2$

Equivalent 2020 emissions: 39 $GtCO_2$.RCP 6.0 was interpolated from RCP 4.5 and RCP 7.0.

§5.2: Expected Economic Damages:

- Terrestrial effects are difficult to assess: hotter but wetter. Uneven.
- More energetic weather phenomena.
- Sea level effects: 400 million displaced, primarily in Bangladesh and Indonesia.

§5.6: Dangers:

- Fast speed of increase.
- Dormant feedback loops.
- Tipping points.
- (Very rare asteroids, supervolcanos)

Chapter 6: Economics

§6.3: Social Cost of CO_2:

- Also optimal tax on CO_2:
  - more $\Rightarrow$ curtail too much.
  - less $\Rightarrow$ pollute too much.
- Sequestration cost is one ceiling to SCC.
- Many problems: judging harm, inefficient administration, corrupt administration, differential harm, escape.

See §6.2: GDP by Region (2020)			
	Total (t$)		pPpY
OECD	$52.3	62%	$38,000
USA	$20.9	25%	$63,000
Europe	$15.3	18%	$34,200
not OECD	$32.4	38%	$5,000
China	$14.7	17%	$10,400
India	$2.7	3%	$1,900
Sub-S Africa	$2.1	2%	$1,500
World	$84.7	100%	$10,900

Estimates can vary. The IMF estimate of world GDP for 2021 is $94 trillion. The population estimate for 2021 is 7.9b (8.0b for 2022).

See GDP Forecasts, PwC			
	In US$	in PPP	
	2020	2020	2050e
OECD	62%		$< 50\%$
USA	25%	16%	12%
Europe	18%	15%	9%
Not OECD	38%		$> 50\%$
China	17%	18%	20%
India	3%	7%	15%
World	100%	100%	100%

§6.5.5: **Marginal Thinking and Cost/Benefit**:

- COP are not about eliminating global warming but about reducing it by "10–20%."
  - Consider RCP 6 to RCP 4.
  - Reduction of global warming by 2050 by 5% (from about 1.7°C to about 1.6°C).
  - Reduction of global warming by 2100 by 20% (from about 3°C to about 2.6°C).
- Est. required reduction: ≈ 15 $GtCO_2$/year.
- 4–5 $GtCO_2$ for each 0.1°C reduction by 2100.
- All US CO_2 emissions: 4.7 $GtCO_2$.
- 15 $GtCO_2$ at $50/$tCO_2$ about $750 billion:
  - About 1% of World GDP. About $100 per person per year.
  - About 1.5% of OECD GDP. About $500 per OECD inhabitant.
  - About 3.5% of US GDP. About $2,000 per US resident.
  - About size of US military spending.
  - About size of US Public School education spending.
- $50 SCC is reducible through (a) smart ramping up of CO_2 tax; (b) smart delay (better tech).

(Warning: All above numbers are immensely huge.)

§6.3: Cost Concepts:

- Diminishing Returns;
- Sunk Costs;
- Learning Curves (FOAK);
- Returns to Scale;
- Optimal Delay.

See Fig 2 and 3: Important Scenarios

		Nordhaus			RCP	
	Year	Base	Prefers	“2°C”	4.5	7.0
CO_2 Tax	2020	\$0	\$45	\$60		
	2050e	\$0	\$110	\$150		
	2100e	\$0	\$300	\$500		
Welfare	2020	0	–0.15%	–0.14%		
	2050e	0	–0.23%	–0.53%		
	2100e	0	+0.42%	–0.71%		
Emissions (CO_2)	2020	39 Gt	33 Gt	32 Gt	39 Gt	39 Gt
	2050e	60 Gt	40 Gt	34 Gt	45 Gt	60 Gt
	2100e	71 Gt	16 Gt	–10 Gt	10 Gt	80 Gt
Temp	pre-ind	≈ –0.45°C				
	1980	0.0°C				
	2020	1.0°C				
	2050e	2.1°C	2.0°C	2.0°C	1.5°C	1.7°C
	2100e	4.1°C	3.5°C	3.3°C	2.5°C	3.6°C

Chapter 7: IAMs

See Tbl 5: $50/tCO$_2$ Tax

Product	Cost Change
Oil & Gasoline	+50%
Coal	+400%
Natgas	+100%
Tree	–\$3/tree

§7.4: Key IAMs Issues:

- sensitivity to discount rate.
- estimating future parameters.
- uncertainty and risk.
- omitted choices: population, income inequality, opportunity costs of other philanthropic activities.

Chapter 8: The Wrong Question

Irrelevant:

- Problem is understanding choices by decision-makers.
- World outcome is *not* the engineered solution to a world problem.
- OECD countries are no longer big enough to solve the problem.
- Non-OECD countries are too poor to fight it.

Chapter 9: Fantasy

Key Problems:

- §9.2: A global (SCC) carbon tax is impossible without a global government.
- §9.3: Treaties not in self-interest. Excludability and free-riding incentives. No similar treaty ever effective.
- §6: Carbon footprints have been known for decades. (Carbon-shaming or setting an example?) What will change?
- What will change? Need to convince 8–11 billion people, not just 25% of the (more climate-conscious) population in the 25% that the OECD represents.

Chapter 10: Reality

Best *Viable* Choices:

- §10.1: Adaptation.
- §10.2: Locally justifiable fossil-fuel taxes (PM Health costs: \$10/tCO_2 to \$100/tCO_2).
- §10.3: Clean Technology.
- §14.2: Reforestation with lumber harvesting.

Chapter 11: Fossil Fuels Vs.

§11.2: Fossil Fuels:

- Achilles Heel: High mining and transport costs;
- 75% of fossil-fuel primary energy ends up as waste heat.
- Primary energy vs. Nameplate Power.
- PM Health costs: \$10/tCO_2 to \$100/tCO_2.

Fossil Fuel Alternatives:

- §11.3: **Hydrogen**: similar to NatGas, but likely far too expensive for many decades.
- §11.4: **Nuclear Power**: • 1 Meltdown / 3,704 reactor years; • 500 (old) nuclear power plants worldwide; • waste disposal solution; • need safer reactors (pebble-bed?).
- §11.5: **(Li) Batteries** • $<1/10$ energy density of fossil fuels, but reusable; • High power, Low capacity; • Almost perfectly in/out-efficient; • Tiny capacity on grid ($\approx$ 10 min total); • Expensive.

§11.7: Propaganda Clarifications:

- Most clean-tech in lab will fail (true), but there are dozens of exciting techs in lab.
- All numbers are immensely large — think 1/10 of all agriculture.
- Space and materials needed for clean tech, but plenty are available *long-run*.
- Clean-tech enjoys some subsidies, though small compared to fossil fuels.
- Expect bumps on the road.

Chapter 12: Electricity

§12.3: Fundamentals:

- High-quality energy. Jack of all trades. High conversion efficiency to kinetic energy.
- Typical daily electricity demand pattern today: Low at noon; Peaks at 7am and 8pm.
- Typical clean-energy supply: High at noon, low at 7am and 8pm.

See Tbl 5: LCOE per MWh

	2020	2050e
Solar	$35	$15
Wind	$35	$20
Nuclear	$70	$60
Natgas, 24/7	$40	$45
Natgas, Peaker	$200	$200
Coal	$75	$65
Hydro	$55	

Costs are in 2020-$ and representative utility-scale but vary by location.

See Tbl 6: Coal Plant Status 2022, in GW

	Oprtg	Cnstrct	Prmt	Anncd
OECD	501.0	16.0	5.0	3.9
USA	232.8	-	-	-
Europe	117.8	12.2	-	-
China	1,046.9	96.7	43.0	72.1
India	233.1	34.4	11.7	11.7
All others	≈280	≈37	≈20	≈24
World	2,067.7	184.5	78.9	111.8

See Tbl 8: Storage Cost, 2030e

	Cost per MWh
Batteries	$120 or $200-$250
Natgas Peaker	$100-$200
Pumped Hydro	$130
Compressed Air	$100

See Fig 9: Needed Grid E-Storage

% Clean Elec	Needed Hours
50%	1 hour
80%	10 hours
90%	100 hours
100%	1,000 hours
Currently	minutes

See Tbl 11: E-Generation in TWh				
Region	Year	USA	China	World
Coal	2020	774	4,313	8,244
	2050e	593	3,556	8,115
NatGas	2020	1,636	267	6,458
	2050e	1,953	803	7,306
Nuclear	2020	785	331	2,630
	2050e	594	1,002	3,025
Hydro	2020	283	1,117	4,034
	2050e	294	1,448	5,548

See left				
Region	Year	USA	China	World
Wind	2020	343	574	1,741
	2050e	790	1,001	6,833
Solar	2020	132	281	832
	2050e	1,072	3,379	10,152
Total	2020	4,061	6,893	24,991
	2050e	5,458	11,230	41,953

These are secondary energy estimates, EIA base scenario.

§12.7: **Transmission**:

- About $2 million per GW per mile.
- Cheap now only because generation is near use. Will become more expensive as generation has to be farther away.
- Giant regulatory mess.

Chapter 13 Beyond Electricity

See Fig 3: Vehicle Use Efficiency			
	Fuel	×Mvng	≈Total
Battery	95%	75%	70%
Hydrogen Fuel Cell	50%	40%	20%
Hydrogen Combustion	45%	30%	13%

Chapter 14: Remediation

Key Points:

- §14.1: Removal cost is one upper ceiling to the Social Cost of Carbon Dioxide.
- §14.2: Reforestation with lumber harvesting is cheapest method, perhaps as low as \$10/tCO_2 for first marginal GtCO_2 (that world is not taking).
- Industrial CO_2 removal projects seem hopelessly expensive for decades to come. Economics work only to arbitrage government subsidies.

- §14.3: Solar radiation management is worth investigating, but not (yet) deploying. Danger of unintended consequences.

Chapter 15: Transition

Favorites:

- Increase innovation.
- Share technology better.
- Tax fossil fuels for local health.
- Forestation.
- Price by supply cost (time).
- Uproot bad habits / nudges.
- Reverse tech lock-in.
- Coordinate transition.
- Reduce green red tape.
- Targeted Federal land leases.
- Kill worst emitters.
- Minor international agreements.

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