

Supplementary Information

The atlas of unburnable oil for supply-side climate policies

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Buffer distance based on health risks associated with oil extraction

Setting a safe distance from oil extraction with respect to health risks is not an easy task. Health effects among people residentially exposed to upstream oil industry contaminants have been poorly studied, particularly in low- and middle-income countries (LMICs)¹. In a systematic review, O'Callaghan-Gordo et al.¹ only found 11 studies examining potential health effects of exposed communities in LMICs. 10 of these studies were conducted in the Ecuadorian and Peruvian Amazon and one in the Niger Delta. The development of unconventional oil and gas projects and the dramatic increase of fracking in the USA in the past decade started to create concern among environmental health researchers² and more environmental health studies are now available regarding fracking in high income countries^{3,4}. Besides the lack of scientific data, the use of sub-standard technologies for oil extraction in LMICs adds a further twist in the difficult task of setting a unique safe distance from oil extraction⁵. Similarly, the different environmental characteristics of the oil extraction locations around the globe makes the identification of a uniform safe distance difficult. Globally, there are an estimated 70,000 oil fields across ~100 countries³. In the case of shale gas drilling, Texas (USA) permits drilling 200 ft (approx. 60 m) from residences. However, many municipalities in Texas have established longer setback distances (setback distances from residences range from 300 to 1500 ft, approx. 90 to 460 m)⁶. Setback distances in Texas have increased over time, and, according to Fry, rather than technically-based, setbacks are political compromises: "rigorous and empirical research was not utilized to determine or demarcate 'safe' or 'healthy' distances, and the setback distances are highly politicized compromises between residents' concerns about the proximity of gas wells to their homes, mineral owners' rights to profit from gas drilling, and the city council's fear of legal lawsuits for a regulatory takings"⁶. In fact, McKenzie et al.⁷ found that residents living within 0.8 km from a fracking well are at a higher health risk than those farther away with benzene as the major contributor to the risk. Coons et al.⁸ also found that significant ambient benzene emissions exist within close proximity to a fracking well (0.8 km), which resulted in significant public health problems. Methane concentrations in drinking water wells within 1 km of a fracking well can reach potentially explosive levels⁹. A recent working paper suggested that a distance within at least 2.5 km from a gas well is detrimental to fetus development due to exposure to shale gas extraction¹⁰. In the USA, a proximity within 1 km to a fracking well is a recurring critical value used for significant risks to the environment and public health. Ref¹¹ used the distances 1 km, 2 km, and 3 km as break values to group risk levels into high (≤ 1 km), moderate (1–2 km), and low (2–3 km) risks. Beyond 3 km, Meng¹¹ assumed there was little impact of fracking wells on the environment and inhabitants in the USA. However, a much more recent review of epidemiological research on

unconventional oil and gas development and health outcomes (all of them conducted in the USA or Australia) showed detectable health effects in distances of up to 10 miles (aprox. 16km) ⁴.

In the very few studies that exist in LMICs, larger distances are suggested. O’Callaghan-Gordo et al.¹², found that increased distance between residence and an oil processing facility (i.e. oil wells, central production facilities, gathering stations and pumping stations) in the Peruvian Amazon was associated with lower Blood Lead Levels (BLL)¹². The median distance from the studied communities to a processing facility was 5.5km, and BLL decreased 5% every 10km up to 200km distance from the oil facilities. A study in south-eastern Bolivia that measured the levels of total petroleum hydrocarbons (TPH), polycyclic aromatic hydrocarbons (PAH), and 22 metals in the drinking water of residents living ≤30 km from an oil extraction field found that three-quarters of the samples were contaminated with concentrations exceeding the reference levels¹³. Similarly, a meta-analysis of chemical data from governmental institutions and oil company reports proved that the dumping of produced water (i.e. the main waste product of oil extraction operations) increased lead, cadmium, chromium and barium concentrations in rivers of the Peruvian Amazon up to 36km downstream of the oil facilities¹⁴.

Differences of unburnable regional oil estimates between studies

When compared to the regional distribution of unburnable conventional resources proposed by Welsby et al.¹⁵, the exclusion zones of this study produce lower proportions of unburnable conventional oil resources (as expected since globally they also concern less resources) with the greatest difference for Canada (2% and 82% unburnable conventional resources in our analysis and Welsby et al. 2021, respectively) and the exception of Developing Asia (outside of China and India; 78% and 48% unburnable conventional resources in our analysis and Welsby et al. 2021, respectively). The regions with large differences are indicative of a divergence between the socio-environmental criteria we employed to identify unburnable resources and the economic ones used by Welsby et al. 2021.

Supplementary Table 1. Burnable and unburnable fossil fuels by 2050 based on data from Welsby et al.¹⁵. This distribution of unburnable fossil fuels categories is based on the supply costs of different fossil fuel resources, taking into account extraction, refining, and transport costs, and using a remaining carbon budget of 580 GtCO₂ under a global 1.5°C target¹⁵. Oil volumes are provided in giga-barrels (Gbbl), gas in cubic terameters (Tm³) and coal in gigatons (Gt).

			Burnable			Unburnable			
						GtCO ₂			
Reserves	Oil	Total	539 Gbbl	42%	232	744 Gbbl	58%	320	
	Gas		64 Tm ³	41%	124	92 Tm ³	59%	178	
	Coal		102 Gt	11%	204	826 Gt	89%	1653	
Resources	Oil	Conventional	752 Gbbl	29%	323	1823 Gbbl	71%	784	
		Unconventional	11 Gbbl	1%	5	1513 Gbbl	99%	651	
		Total	783 Gbbl	19%	336	3336 Gbbl	81%	1434	
	Gas	Conventional	79 Tm ³	19%	152	341 Tm ³	81%	661	
		Unconventional	22 Tm ³	7%	42	284 Tm ³	93%	551	
		Total	102 Tm ³	14%	197	625 Tm ³	86%	1212	
	Coal		122 Gt	3%	245	3960 Gt	97%	7927	

Supplementary Table 2. List of countries in each of the 10 regions presented. Extracted from Welsby et al.¹⁵.

<u>Region</u>	<u>Countries</u>
<u>Africa</u>	Algeria, Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Congo, Côte d'Ivoire, Democratic Republic of the Congo, Djibouti, Egypt, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Libya, Madagascar, Malawi, Mali, Mauritania, Morocco, Mozambique, Namibia, Niger, Nigeria, Rwanda, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Somalia, South Africa, South Sudan, Sudan, Swaziland, Togo, Tunisia, Uganda, United Republic of Tanzania, Zambia, Zimbabwe
<u>Australia and other OECD Pacific</u>	Australia, Japan, New Zealand, Republic of Korea
<u>Canada</u>	Canada
<u>China and India</u>	China, Taiwan, Tibet, India
<u>Russia and former Soviet states</u>	Armenia, Azerbaijan, Belarus, Estonia, Georgia, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Republic of Moldova, Russian Federation, Tajikistan, Turkmenistan, Ukraine, Uzbekistan
<u>Central and South America</u>	Anguilla, Antigua and Barbuda, Argentina, Aruba, Bahamas, Barbados, Belize, Bermuda, Bolivia, Brazil, Cayman Islands, Chile, Colombia, Costa Rica, Cuba, Dominica, Dominican Republic, Ecuador, El Salvador, Falkland Islands, Grenada, Guatemala, Guyana, Haiti, Honduras, Jamaica, Martinique, Mexico, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and the Grenadines, Suriname, Trinidad and Tobago, Uruguay, Venezuela (Bolivarian Republic of)
<u>Europe</u>	Albania, Andorra, Austria, Belgium, Denmark, Faroe Islands, Finland, France, Germany, Gibraltar, Greece, Greenland, Iceland, Ireland, Italy, Luxembourg, Malta, Monaco, Netherlands, Norway, Portugal, San Marino, Spain, Sweden, Switzerland, United Kingdom, Vatican, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, Hungary, Montenegro, Poland, Romania, Serbia, Slovakia, Slovenia, The former Yugoslav Republic of Macedonia
<u>Middle East</u>	Bahrain, Brunei Darussalam, Cyprus, Iran (Islamic Republic of), Israel, Jordan, Kuwait,

<u>Region</u>	<u>Countries</u>
	Lebanon, Occupied Palestinian Territory, Oman, Qatar, Saudi Arabia, Syrian Arab Republic, Turkey, United Arab Emirates, Yemen
<u>Other Developing Asia</u>	Afghanistan, American Samoa, Bangladesh, Bhutan, Cambodia, Democratic People's Republic of Korea, Fiji, French Polynesia, Indonesia, Kiribati, Laos, People's Democratic Republic, Malaysia, Maldives, Mauritius, Mongolia, Myanmar, Nepal, New Caledonia, Pakistan, Papua New Guinea, Philippines, Samoa, Singapore, Solomon Islands, Sri Lanka, Thailand, Timor-Leste, Tonga, Vanuatu, Vietnam
<u>USA</u>	United States of America

Supplementary Table 3. List of top sedimentary basins containing the highest amount of unburnable conventional oil resources according to socio-environmental criteria. Cumulative percentage of unburnable resources and intersected area per each sedimentary basin is provided. Volumes are given in giga-barrels (thousand million oil barrels, Gbbl).

Sedimentary Basins	Oil resources overlapped (Gbbl)	Cumulative top-priority unburnable oil resources (%)	Intersected area (km²)	Cumulative area intersected (km²)	Cumulative area intersected (%)
Zagros Fold Belt	70.79	12%	234,465	234,465	1%
Gulf Coast Basins	59.73	21%	598,505	832,970	3%
Mesopotamian Foredeep Basin	58.07	31%	61,136	894,107	3%
Maracaibo Basin	21.93	35%	44,009	938,116	3%
West Siberian Basin	21.84	38%	259,254	1,197,369	4%
Rub Al Khali Basin	16.78	41%	108,623	1,305,993	4%
Northern Alaska	14.99	43%	137,977	1,443,970	5%
Greater Ghawar Uplift	14.41	46%	12,864	1,456,834	5%
Villahermosa Uplift	13.48	48%	12,686	1,469,519	5%
Niger Delta	12.88	50%	90,990	1,560,509	5%

Sedimentary Basins	Oil resources overlapped (Gbbl)	Cumulative top- priority unburnable oil resources (%)	Intersected area (km2)	Cumulative area intersected (km2)	Cumulative area intersected (%)
Appalachian Basin	11.97	52%	170,401	1,730,910	6%
Morondava	11.53	54%	416,921	2,147,832	7%
Red Sea Basin	11.25	56%	488,511	2,636,342	9%
Permian Basin	9.13	57%	11,646	2,647,988	9%
East Venezuela Basin	8.65	59%	122,025	2,770,013	9%
Santos Basin	8.32	60%	49,779	2,819,793	10%
West-Central Coastal	8.19	61%	114,202	2,933,994	10%
Central Sumatra Basin	8.16	63%	118,070	3,052,065	10%
Bohaiwan Basin	7.91	64%	99,992	3,152,056	11%
Burgos Basin	6.57	65%	48,485	3,200,541	11%
Greater Antilles Deformed Belt	6.33	66%	517,814	3,718,355	13%
Campos Basin	6.16	67%	33,669	3,752,024	13%
East African Rift	6.12	68%	1,326,637	5,078,661	17%
Middle Magdalena Valley Basin	5.89	69%	31,828	5,110,489	17%
Mozambique Coastal	5.54	70%	370,093	5,480,581	19%
Volga-Ural Region	5.50	71%	145,904	5,626,485	19%
Tampico-Misantla Basin	5.46	72%	27,026	5,653,511	19%
South Sumatra Basin	5.24	73%	134,523	5,788,034	20%
Parana Basin	5.20	74%	1,155,217	6,943,251	24%
Sud Province	4.93	74%	268,874	7,212,125	24%

Sedimentary Basins	Oil resources overlapped (Gbbl)	Cumulative top- priority unburnable oil resources (%)	Intersected area (km2)	Cumulative area intersected (km2)	Cumulative area intersected (%)
Tanzania Coastal	4.87	75%	243,210	7,455,336	25%
North Caspian Basin	4.70	76%	71,879	7,527,215	25%
Middle Caspian Basin	4.07	77%	178,270	7,705,485	26%
Neuquen Basin	4.05	77%	32,936	7,738,421	26%
Junggar Basin	3.74	78%	31,265	7,769,685	26%
South Caspian Basin	3.72	79%	30,950	7,800,635	26%
Kutei Basin	3.42	79%	213,249	8,013,884	27%
Qatar Arch	3.39	80%	14,082	8,027,966	27%
Putumayo-Oriente-Maranon Basin	3.35	80%	245,173	8,273,139	28%
Indus	3.31	81%	263,413	8,536,553	29%
Trias/Ghadames Basin	3.10	81%	40,645	8,577,198	29%
Essaouni Basin	2.97	82%	32,871	8,610,069	29%
Baram Delta/Brunei-Sabah Basin	2.91	82%	117,348	8,727,417	30%
Llanos Basin	2.90	83%	114,040	8,841,457	30%
Canning Basin	2.85	83%	118,211	8,959,668	30%
Malay Basin	2.74	84%	147,265	9,106,933	31%
Anglo-Paris Basin	2.74	84%	109,708	9,216,642	31%
Williston Basin	2.59	84%	65,142	9,281,783	31%
Santa Cruz-Tarija Basin	2.44	85%	187,242	9,469,025	32%
Parnaiba Basin	2.35	85%	403,677	9,872,702	33%
Bombay	2.34	86%	129,435	10,002,137	34%

Sedimentary Basins	Oil resources overlapped (Gbbl)	Cumulative top- priority unburnable oil resources (%)	Intersected area (km2)	Cumulative area intersected (km2)	Cumulative area intersected (%)
Northwest Java Basin	2.26	86%	141,795	10,143,932	34%
Denver Basin	2.21	86%	17,307	10,161,239	34%
Anglo-Dutch Basin	2.10	87%	82,135	10,243,375	35%
North Sea Graben	2.03	87%	12,938	10,256,313	35%
Gulf of Guinea	1.92	87%	47,590	10,303,903	35%
Assam	1.88	88%	90,769	10,394,673	35%
Northwest Shelf	1.86	88%	303,994	10,698,667	36%
Songliao Basin	1.82	88%	30,218	10,728,885	36%
Sirte Basin	1.74	89%	22,337	10,751,222	36%
Chad	1.68	89%	316,041	11,067,263	37%
Cauvery	1.57	89%	149,808	11,217,071	38%
Carpathian-Balkanian Basin	1.47	89%	74,299	11,291,370	38%
East Greenland Rift Basins	1.45	90%	30,261	11,321,631	38%
	...	...	...	...	...
Total	608.81	100%		29,540,905.53	100%

Supplementary Table 4. Global oil extraction between 2000 and 2022 disaggregated per country¹⁶. Cumulative production is presented in giga-barrels (thousand million barrels, Gbbl).

[illegible]

Country	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	Total production (Gbbt)
Mauritania	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04
Mauritius	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mexico	1.26	1.30	1.31	1.39	1.40	1.38	1.35	1.28	1.16	1.09	1.09	1.08	1.07	1.06	1.03	0.95	0.90	0.82	0.76	0.70	0.71	0.72	0.74	24.57
Micronesia	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Moldova	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mongolia	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Montserrat	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Morocco	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mozambique	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Namibia	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nauru	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nepal	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Netherlands	0.03	0.03	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.02	0.02	0.02	0.03	0.03	0.03	0.03	0.02	0.02	0.02	0.03	0.03	0.03	0.03	0.67
Netherlands Antilles	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
New Caledonia	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
New Zealand	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.34
Nicaragua	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Niger	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.06
Nigeria	0.79	0.83	0.78	0.83	0.85	0.96	0.89	0.86	0.79	0.81	0.90	0.92	0.92	0.86	0.88	0.82	0.71	0.74	0.73	0.74	0.68	0.60	0.52	18.39
Niue	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
North Korea	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
North Macedonia	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Northern Mariana Islands	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Norway	1.22	1.25	1.22	1.19	1.17	1.09	1.02	0.94	0.90	0.86	0.78	0.75	0.70	0.67	0.69	0.71	0.73	0.72	0.68	0.64	0.73	0.74	0.70	20.09

Country	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	Total production (Gbbt)
Yemen	0.16	0.16	0.16	0.16	0.15	0.15	0.14	0.12	0.11	0.10	0.10	0.08	0.06	0.05	0.05	0.02	0.01	0.01	0.02	0.02	0.02	0.02	0.02	1.87
Zambia	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Zimbabwe	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
World	28.37	28.35	28.14	29.06	30.48	31.08	31.13	31.15	31.67	31.29	31.87	32.30	33.13	33.33	34.27	35.27	35.44	35.70	36.68	36.59	34.26	34.94	36.51	751.00

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