Chapter 6: Supplementary Material

Overview of the factors affecting the feasibility of mitigation options in energy systems and how they differ across context (e.g., region), time (e.g., 2030 versus 2050), and scale (e.g., small versus large), and the line of sight on which the feasibility assessment shown in Figure 6.9 is based. The feasibility assessment method is explained in Annex II12 and Box TS.7.

	Geophysical		
	Physical potential	Geophysical resources	Land Use
Solar energy	+	+	±
Role of context	Limited in higher latitudes	Not limited by materials	Limited in urban areas
Line of sight	Dupont, E., R. Koppelaar, and H. Jeanmart, 2020: Global available solar energy under physical and energy return on investment constraints. Appl. Energy, 257, 113968, https://doi.org/10.1016/j.apenergy.2019.113968.	IEA, 2020: Clean energy progress after the Covid-19 crisis will need reliable supplies of critical minerals – Analysis - IEA. https://www.iea.org/articles/clean-energy-progress-after the covid-19-crisis-will-need-reliable-supplies-of critical-minerals (Accessed August 20, 2020).	Tröndle, T., 2020: Supply-side options to reduce land requirements of fully renewable electricity in Europe. *PLoS One*, **15**, e0236958, https://doi.org/10.1371/journal.pone.0236958.
Wind energy	+	+	±
Role of context	Unevenly distributed over the globe and the time of the year	Not limited by materials	Limited in some areas (e.g., Europe), but large regional variations
Line of sight	McKenna et al (2021): High-resolution large-scale onshore wind energy assessments: a review of potential definitions, methodologies and future research needs. Renewable Energy 183, 759-684. https://doi.org/10.1016/j.renene.2021.10.027	Rohrig, K., and Coauthors, 2019: Powering the 21st century by wind energy—Options, facts, figures. Appl. Phys. Rev., 6, 031303, https://doi.org/10.1063/1.5089877.	Tröndle, T., 2020: Supply-side options to reduce land requirements of fully renewable electricity in Europe. *PLoS One*, **15**, e0236958, https://doi.org/10.1371/journal.pone.0236958.
Hydroelectric power	±	+	±
Role of context	Limited in water scarce regions and where good suitable locations are taken also could be impacted by climate change	Not limited by materials to build dams	Covering large land areas with water

Line of sight	Banerjee et al. (2017); Hoes et al. (2017); Van Vliet et al. (2016); Zhou et al. (2015) Hoes, O. A. C., L. J. J. Meijer, R. J. van der Ent, and N. C. van de Giesen, 2017: Systematic high-resolution assessment of global hydropower potential. PLoS One, 12, e0171844, https://doi.org/10.1371/journal.pone.0171844. Zhou, Y., M. Hejazi, S. Smith, J. Edmonds, H. Li, L. Clarke, K. Calvin, and A. Thomson, 2015: A comprehensive view of global potential for hydro-generated electricity. Energy Environ. Sci., 8, 2622–2633, https://doi.org/10.1039/C5EE00888C.	Shibao Lu, Weidong Dai, Yao Tang, Min Guo (2020). A review of the impact of hydropower reservoirs on global climate change, Science of The Total Environment, Volume 711, 2020, 134996, https://doi.org/10.1016/j.scitotenv.2019.134996. Tremblay, A., Varfalvy, L., Roehm, C., Garneau, M. (2020). Greenhouse Gas Emissions - Fluxes and Processes: Hydroelectric Reservoirs and Natural Environmen s. Jacobson, Mark Z., Mark A. Delucchi (2011). Providing all global energy with wind, water, and solar power, P rt I: Technologies, energy resources, quantities and areas of infrastructure, and materials. Energy Policy, Volume 39, Issu 3 Pages 1154-1169, https://doi.org/10.1016/j.enpol 2010 11.040.	Romanos Ioannidis and Demetris Koutsoyiannis (2020). A review of land use, visibility and public perception of renewable energy in the context of landscape impact. Applied Energy, Volume 276, 15 October 2020, 115367, https://doi.org/10.1016/j.apenergy.2020.115367 A M. Trainor, R.I. McDonald, J. Fargione (2016). Energy Sprawl Is the Largest Driver of Land Use Change in United States. PLoS ONE, 11, 10.1371/journal.pone.0162269 Anne M. Trainor, Robert I. McDonald, Joseph Fargione (2016). Energy Sprawl Is the Largest Driver of Land Use Change in United States. https://doi.org/10.1371/journal.pone.0162269
Nuclear	±		+
Role of context	Physical potential is not an issue. Existing sites could be reused, new sites can be identified and only few countries might face space limitations	Sufficient resources for deployment at meaningful scales	Has low footprint for land. Some point out to the longevity of permanent storage for high level radioactive waste, which has a long span in utilisation but still very low footprint in land use
Line of sight	Damoom, M. M., et al., Potential areas for nuclear power plants siting in Saudi Arabia: GIS-based multi-criteria decision making analysis, Progress in Nuclear Energy Volume 110, January 2019, Pages 110-120, https://doi.org/10.1016/j.pnuc ne.2018 0 9.018 Zhang, X.Y. et al., Perspective on Site Selection of Small Modular Re ctors, Journal of Environment l Informatics Letters 3(1) 39-48 (2020), doi:10.3808/jeil.202000026	OECD NUCLEAR ENERGY AGENCY and INTERNATIONAL ATOMIC ENERGY AGENCY, 2019: Uranium 2018: Resources, Production and Demand, OECD Publishing, Paris.	FTHENAKIS, V., KIM, H.C., Land use and electricity generation: A life-cycle analysis, Renew. Sustain. Energy Rev. 13 (2009) 1465–1474; G. Luderer, M. Pehl, A. Arvesen, T. Gibon, B.L. Bodirsky, H.S. de Boer, O. Fricko, M. Hejazi, F. Humpenöder, G. Iyer, 2019: Environmental co-benefits and adverse side-effects of alternative power sector decarbonization strategies, Nat. Commun., 10 (2019), pp. 1-13; Cheng, V.K.M., Hammond, G.P., 2017: Life-cycle energy densities and land-take requirements of various power generators: A UK perspective, Journal of the Energy Institute, vol. 90, iss. 2, pp. 201-213. https://doi.org/10.1016/j.joei.2016.02.00

Carbon Dioxide Capture, Utilization, and Storage	±	±	+
Role of context	Limited in some sectors - including CO_2 utilization, bioenergy with CCS etc.	Limited in some sectors - including CO_2 utilization, bioenergy with CCS etc.	Less than several other mitigation options (not considering bioenergy)
Line of sight	Budinis, S., Krevor, S., Mac Dowell, N., Brandon, N., & Hawkes, A. (2018). An assessment of CCS costs, barriers and potential. Energy strategy reviews, 22, 61-81.; Selosse, S., & Ricci, O. (2017). Carbon capture and storage: Lessons from a storage potential and localization analysis. Applied Energy, 188, 32-44.		
Bioenergy	+	NA	-
Role of context	Very large physical potential. Wastes and residues (e.g., from agricultural, forestry, animal manure processing) or biomass grown on degraded, surplus, and marginal land can provide opportunities for cost-effective and sustainable bioenergy at significant but limited scale. A major scale-up of bioenergy production will require dedicated production of advanced biofuels. Assessing the potential for a major scale-up of purpose-grown bioenergy is challenging due to its far-reaching linkages to issues beyond the energy sector, including competition with land for food production and forestry, water use, impacts on ecosystems, and land-use change). These factors, rather than geophysical characteristics, largely define the potential for bioenergy.	Not limited by materials	Potentially large land use implications but depends on scale and bioenergy feedstocks.
Line of sight	Roe, S., Streck, C., Beach, R., Busch, J., Chapman, M., Daioglou, V Deppermann, A., Doelman, J Emmet-Booth, J., Engelmann, J. and Fricko, O , 2021. Land-based m asures to mitig te climate change: Potential and feasibility by country. Global Change Biology. Slade, Raphael, Ausilio Bau n, and Robert Gross. "Global bioene gy resources." *Nature Climate Change* 4, no. 2 (2014): 99-105.	Hanssen, S.V., Daioglou, V., Steinmann, Z.J., Frank, S., Popp, A., Brunell , T., Lauri, P., Hasegawa, T., Huijbregts, M.A. and Van Vuuren, D.P., 2020. Biomass residues as twenty-first century bioenergy feedstock—a comparison of eight integrated assessment models. Climatic Change, 163(3), pp.1569-1586.	Strapasson, A., Woods, J., Chum, H., Kalas, N., Shah, N., & Rosillo-Calle, F. (2017). On the global limits of bioenergy and land use for climate change mitigation. Gcb Bioenergy, 9(12), 1721-1735. Smith, P., and Coauthors, 2019: Chapter 6 : Interlinkages between Desertification , Land Degradation , Food Security and GHG fluxes : synergies , trade-offs and Integrated Response Options Table of Contents. *Ipcc*, P.R. Shukla et al., Eds., 1–147.

	Fuss, S., Lamb, W.F., Callaghan, M.W., Hilaire, J., Creutzig, F., Amann, T., Beringer, T., de Oliveira Garcia, W., Hartmann, J., Khanna, T. and Luderer, G., 2018. Negative emissions—Part 2: Costs, potentials and side effects. *Environmental Research Letters*, *13*(6), p.063002.		IPCC, 2019: Summary for Policy Makers. *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*, P.R. Shukla et al., Eds.
Fossil fuel phaseout	NA	+	±
Role of context	Large physical resource to remain unutilized	Mining and depletion of non-renewable resources would reduce	Uncertain but could be positive if it reduces the need for CDR
Line of sight	McGlade, C., & Ekins, P. (2015). The geographical distribution of fossil fuels unused when limiting global warming to 2 C. Nature, 517(7533), 187-190.	Luderer, G., Pehl, M., Arvesen, A., Gibon, T., Bodirsky B. L., de Boer, H. S., ... & Mima, S. (2019). Environmental co-benefits and adverse side-effects of altern tive power sector decarbonization strategies. Nature commun cations, 10(1) 1 13.	Kriegler, E., Bauer, N., Popp, A., Humpenöder, F., Leimbach, M., Strefler, J., ... & Mouratiadou, I. (2017). Fossil-fueled development (SSP5): an energy and resource intensive scenario for the 21st century. Global environmental change, 42, 297-315.
Geothermal	-	+	+
Role of context	Large potential but very site specific. Up-front cost particularly high and associated with uncertainties for drilling	For direct thermal uses, the technical potential is estimated at 10 to 312 EJ/yr (IPCC 2011). For electrici y generation, technical potential is estim ted between 118 EJ/yr (to 3 km depth) and 1,109 EJ/yr (to 10 km depth)	Little impact on land use
Line of sight	IPCC, (2011)	IPCC (2011)	Trevor M. Hunt, 2001, Institute of Geological and Nuclear Sciences, Taupo, New Zealand.
Energy storage for low-carbon grids	-	+	±
Role of context	The size of grid networks, cus omer demands, storing capacity and location of devices, their advantages and limitations, cost, lifetime, and impacts on the environment must be considered during selection decision. The sourc s of power produ tion; r newable or fossil fuels, must also be accounted, as well as the integration with incumbent systems.	Due to a wide range of technologies, it is available.	Depends on type of storage, some require considerable amounts of land.
Line of sight	Shaqsi et l., (2020)	EPA, (2019)	Shaqsi et al., (2020) Ozarslan, (2012)
Demand side mitigation	NA	NA	NA

Role of context			
Line of sight		-	-
System integration	-	0	0
Role of context	This requires tapping newly developed integration facilities, such as facilities that combine hardware testing at proper scale with simulation. Monitoring is also challenging due to big data.		
Line of sight	Kroposki et al., (2012)		

	Environmental-ecological			
	Air pollution	Toxic waste, ecotoxicity eutrophication	Water quantity and quality	Biodiversity
Solar energy	+	±	+	±
Role of context	Minimal effects in manufacturing	Low when recycled properly		Concerns in protected areas
Line of sight	Mahmud, M. A. P., N. Huda, S. H. Farjana, and C. Lang, 2018: Environmental impacts of solar-photovoltaic and solar-thermal systems with life-cycle assessment. *Energies*, https://doi.org/10.3390/en11092346.	Heath, G. A., and Coauthors, 2020 Research and development priorities for silicon photovoltaic module recycling to support a circular economy. Nat. Energy, 5, 502–510, https://doi.org/10.1038/s41560-020-0645-2. Mahmud, M. A. P., N. Huda, S. H. Farjana, and C. Lang, 2018: Environmental impacts of solar-photovoltaic and solar-thermal systems with life-cycle assessment. *Energies*, https://doi.org/10.3390/en11092346.	Mahmud, M. A. P., N. Huda, S. H. Farjana, and C. Lang, 2018: Environmental impacts of solar-photovoltaic and solar-thermal systems with life-cycle assessment. *Energies*, https://doi.org/10.3390/en11092346.	Hernandez, R. R., M. K. Hoffacker, M. L. Murphy-Mariscal, G. C. Wu, and M. F. Allen, 2015: Solar energy development impacts on land cover change and protected areas. Proc. Natl. Acad. Sci., 112, 13579–13584, https://doi.org/10.1073/pnas.1517656112 .
Wind energy	+	±	+	±
Role of context	Minimal effects in manufacturing	Low when recycled properly		Can be minimized by careful site selection of wind power facilities
Line of sight	Sovacool et al., (2016). Wind Energy, DOI: 10.1002/we.1941; Wang et al (2020), http://dx.doi.org/10.1016/j.rser.2015.01.031			
Hydroelectric power	+	-	-	-
Role of context	A clean energy option, but some emission from concrete to construct dams, and emissions from the water buddies	Water impoundments behind dams lead to eutrophication and release of contaminants from sediments.	Affect hydrologic flows, water temperature in streams, and downstream habitat	Damages habitat, thermal pollution, hypoxia, fish migration, increased water consumption/evaporation

Line of sight	(Prairie et al. 2018, Phyoe and Wang 2019; Maavara et al. 2020) Xingcheng Yan, Vincent Thieu, Josette Garnier (2021). Long-Term Evolution of Greenhouse Gas Emissions From Global Reservoirs. Front. Environ. Sci., https://doi.org/10.3389/fenvs.2021.705477 L. Gagnon, J.F. van de Vate, Greenhouse gas emissions from hydropower: the state of research in 1996. Energy Policy, 25 (1997), pp. 7-13	Rietzler, A.C., Botta, C.R., Ribeiro, M.M. et al. Accelerated eutrophication and toxicity in tropical reservoir water and sediments: an ecotoxicological approach. Environ Sci Pollut Res 25, 13292–13311 (2018). https://doi.org/10.1007/s11356-016-7719-5	Cronin, J., Anandarajah, G. & Dessens, O. Climate change impacts on the energy system: a review of trends and gaps. Climatic Change 151, 79–93 (2018). https://doi.org/10.1007/s10584-018-2265-4 Turner, S. W. D. M. Hejazi, S. H. Kim, L Clarke, and J. Edmonds, 2017: Climate impacts on hydropower and consequences for global ele tricity supply investment n eds. Energy, 141, 2081–2090, https://doi.org/10.1016/j.energy.2017.11.089. van Vliet, M. T. H., L. P. H. van Beek, S. Eisner, M. Flörke, Y. Wada, and M. F. P. Bierkens, 2016a: Multi-model assessment of global hydropower and cooling water discharge potential under climate change. Glob. Environ. Chang., 40, 156–170, https://doi.org/10.1016/j.gloenvcha.2016.07.007. van Vliet, M. T. H., J. Sheffield, D. Wiberg, and E. F. Wood, 2016b: Impacts of recent drought and warm years on water resources and electricity supply worldwide. Environ. Res. Lett., 11, 124021, https://doi.org/10.1088/1748-9326/11/12/124021. Van Vliet, M. T. H., D. Wiberg, S. Leduc, and K. Riahi, 2016: Power-generation system vulnerability and adaptation to changes in climate and	Erik Olav Gracey and Francesca Verones (2016). Impacts from hydropower production on biodiversity in an LCA framework—review and recommendations. Int J Life Cycle Assess (2016) 21:412–428, DOI 10.1007/s11367-016-1039-3 Zarfl, C., Berlekamp, J., He, F. et al. Future large hydropower dams impact global freshwater megafauna. Sci Rep 9, 18531 (2019). https://doi.org/10.1038/s41598-019-54980-8 Premalatha, M., Tabassum-Abbasi, T. Abbasi, and S. A. Abbasi, 2014: A critical view on the eco-friendliness of small hydroelectric installations. Sci. Total Environ., 481, 638–643, https://doi.org/10.1016/j.scitotenv.2013.11.047.

			water resources. Nat. Clim. Chang., 6, 375–380, https://doi.org/10.1038/nclimate2903 Yalew, S. G., and Coauthors, 2020: Impacts of climate change on energy systems in global and regional scenarios. Nat Energy, https://doi.org/10.1038/s41560-020-0664-z. Mukheibir, P., 2013: Potential consequences of projected climate change impacts on hydroelectricity gene ation. Clim. Change, 121, 67–78, https://doi.org/10.1007/s10584-013-0890-5.	
Nuclear	+	±	±	±
Role of context	Has low NOx, SO2, PM, NMVOC emissions on a life-cycle basis	Low impacts to ecosystems (acidificati n, eutrophication, ecotoxicity, ozone depletion, POCP). Long term solutions for high level radioactive waste are under development.	Water withdrawal rates depend a lot on the type of cooling system. Once-through cooling systems need a lot of water, but most of it is returned to freshwater bodies. Withdrawal rates from closed-loop cooling systems are significantly lower as compared to once-through systems.	Low impacts to biodiversity but high impact in case of an accident.
Line of sight	Gibon, T., Hertwich, E. G., Arvesen, A., Singh, B. & Verones, F., 2017: Health benefits, ecological thr ats of low-carbon electricity. Environ Res. L tt. 12, 034023. Joint Research Centre European Commission (JRC EU), 2021. Technical assessment of nuclear energy with respect to the 'do no significant harm criteria of Regulation (EU) 2020/852 (Taxonomy Regulation'),	G. Luderer, M. Pehl, A. Arvesen, T. Gibon, B.L. Bodirsky H.S. de Boer, O. Fricko, M. Hejazi, F. Humpenöder, G. Iyer, 2019: Environmental co-benefits and adverse side-effects of alternative power sector decarbonization strategies, Nat. Commun., 10 (2019), pp. 1-13. Joint Research Centre European Commission (JRC EU), 2021. Technical assessment of nuclear energy with respect to the 'do no significant harm' criteria of Regulation (EU) 2020/852 ('Taxonomy Regulation'),	Meldrum, J., Nettles-Anderson, S., Heath, G., Macknick, J., 2013: Life cycle water use for electricity generation: a review and harmonization of literature estimates, Environ. Res. Lett. 8 015031; Mouratiadou, I., Biewald, A., Pehl, M., Bonsch, M., Baumstark, L., Klein, D., Popp, A., Luderer, G., Kriegler, E., 2016: The impact of climate change mitigation on water demand for energy and food: An	Brook, B.W., Bradshaw, C.J., 2014: Key role for nuclear energy in global biodiversity conservation, Conservation Biology, vol. 29, iss. 3, pp. 702-712. https://doi.org/10.1111/cobi.12433

			integrated analysis based on the Shared Socioeconomic Pathways, Elsevier, Environmental Science & Policy, Volume 64, Pages 48-58. Joint Research Centre European Commission (JRC EU), 2021. Technical assessment of nuclear energy with respect to the 'do no significant harm criteria of Regulation (EU) 2020/852 ('Taxonomy Regulation')	
Carbon Dioxide Capture, Utilization, and Storage	+	0	±	0
Role of context	Reduces air pollution from fossil sector as an indirect advantage based on technological specifications	Depends largely on fuel sources	Water use increases and could lead to plant retirements in several water stressed regions	Depends largely on fuel sources
Line of sight	Rubin, E. S., Chen, C., & Rao, A. B. (2007). Cost and performance of fossil fuel power plants with CO_2 capture and storage. Energy policy, 35(9), 4444-4454.		Liu, L., Hejazi, M., Iyer, G., & Forman, B. A. (2019). Implications of water constraints on electricity capacity expansion in the United States. Nature Sustainability, 2(3), 206-213.	
Bioenergy	±	NE	±	±
Role of context	Direct use of bioenergy without CCS leads to air pollutant emissions. For bioenergy the life cycle assessment of criteria pollutants is considerably different than that for GHGs and the impact of bioenergy use on air pollutants need to be examined on smaller spatial scales and might be more or less significant compared to fossil fuels. Bioenergy with CCS for hydrogen or electricity production offers an opportunity to mitigate pollutants emissions while BECCS for liquid fossil fuels doesn't solve the problem of end-use pollutants emissions at the final point of use.	Can use wastes as a feedstock for bioenergy but the overall impact of bioenergy on toxic waste, ecotoxicity, and eutrophication remains to be assessed.	Depends on scale, feedstock, prior land use, and management practice. If bioenergy is irrigated and produced at a large scale, water use and water scarcity could increase. If fertilized, bioenergy could have implications for water quality. However, if perennial grasses with low N input are planted on previously cropped land, bioenergy could improve water quality.	The impact of bioenergy on biodiversity depends on the initial land use condition, the type of bioenergy production system, and the landscape configuration. The impacts of second-generation bioenergy crops tend to be less negative than first generation ones, and are in some cases positive.

Line of sight	Hess, P., Johnston, M., Brown-Steiner, B., Holloway, T., de Andrade, J.B. and Artaxo, P., 2009. Air quality issues associated with biofuel production and use. Cornell University Library's Initiatives in Publishing (CIP).	Lee, S.Y., Sankaran, R., Chew, K.W., Tan, C.H., Krishnamoorthy, R., Chu, D.T. and Show, P.L., 2019. Waste to bioenergy: a review on the recent conversion technologies. Bmc Energy, 1(1), pp.1-22.	Schyns, J. F., Hoekstra, A. Y., Booij, M. J., Hogeboom, R. J., & Mekonnen, M. M. (2019). Limits to the world's green water resources for food, feed, fiber, timber, and bioenergy. Proceedings of the National Academy of Sciences, 116(11), 4893-4898. Calvin, K., and Coauthors, 2021: Bioenergy for climate change mitigation: Scale and sustainability. *GCB Bioenergy*, **13**, 1346–1371, h tps://doi.org/https://doi.org/10.111 1/gcbb.12863. Section 3.7.3	Immerzeel, D.J., Verweij, P.A., Van Der Hilst, F. and Faaij, A.P., 2014. Biodiversity impacts of bioenergy crop production: A state-of-the-art review. Gcb Bioenergy, 6(3), pp.183-209. Smith, P., Price, J., Molotoks, A., Warren, R., & Malhi, Y. (2018). Impacts on terrestrial biodiversity of moving from a 2 C to a 1.5 C target. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 376(2119), 20160456. Calvin, K., and Coauthors, 2021: Bioenergy for climate change mitigation: Scale and sustainability. *GCB Bioenergy*, **13**, 1346–1371, https://doi.org/https://doi.org/10.1111/gcbb.12863.
Fossil fuel phaseout	+	±	+	+
Role of context	Large air pollution benefits especially of coal phaseout	Considerable benefits but r placements could increase other waste	Uncertain but could be positive if it reduces the need for CDR. Other positive impacts due to reduced needs for fracturing	Improved biodiversity outlook
Line of sight	Rauner, S., Bauer, N., Dirnaichner, A , Van Dingenen, R., Mutel, C., & Luderer, G. (2020). Coal-exit health and environmental damage reductions outweigh economic impacts. Nature Climate Change, 10(4), 308-312.		Oei, P. Y., Hermann, H., Herpich, P., Holtemöller, O., Lünenbürger, B., & Schult, C. (2020). Coal phase-out in Germany–Implications and policies for affected regions. Energy, 196, 117004.	Harfoot, M. B., Tittensor, D. P., Knight, S., Arnell, A. P., Blyth, S., Brooks, S., ... & Scharlemann, J. P. (2018). Present and future biodiversity risks from fossil fuel exploitation. Conservation Letters, 11(4), e12448.
Geothermal	±	±	-	-
Role of context	Geothermal power plants can meet the most stringent clean air standards. But can also eject more heat than other type plants per unit of electricity generated	-	Impact on ground water depletion and contamination, living organisms, seismicity	Impact on living organisms
Line of sight	Trevor M Hunt, (2001), Ins itut of Geological and Nuclear Sciences, Taupo, New Zealand Dowd et al. (2011). Mahmood ARSHAD et al, (2019)			

Energy storage for low-carbon grids	+	-	-	±
Role of context	The storing techniques and devices can also affect the environment positively. The positive impacts may be the decreased impact on global warming and a lesser effect emerging from the use of fossil fuels. Some materials and manufacturing processes do emit GHGs, either directly, or due to the source of the power they use.	Disposal of devices material may also emerge as a constraint to the environment if not deployed and managed appropriately. Some devices use critical resources and materials which are eco-toxic or polluting, particularly during extraction and manufacturing.	The extraction of materials and manufacturing processes for some devices use a considerable amount of fresh water. The wastewater generated during different processes (e.g., manufacturing, treatment, recycling) can be dangerous. If wastewater penetrates into the ground and flows into surface waters, it can create many problems for human health, so capture and treatment of contaminated wastewater is very important and vital.	Direct impacts on ecosystems largely come from material extraction; some devices require more impactful materials than others. Some technologies would directly encroach on ecosystems due to their land use.
Line of sight	(ESA, 2019)	(ESA, 2019)	(Dehghani-Sanj et al., 2019)	(Gajardo & Redón, 2019)
Demand side mitigation	+		+	+
Role of contexts	Impact varies across behaviors and different pollutants.	Using less resources implies producing less toxic waste. Varies across behaviors; circular behavior reduces toxic waste and CO_2 emissions	Some mitigation options would increase water use, such as using nuclear	Low carbon actions protect ecosystems; cook stoves reduce deforestation
Line of sight	https://doi.org/10.1016/j.envint.2018.06 001; https://www.oecd.org/environment/cc/2055676.pdf; see also SR1.5	reference = SR1.5.	SR1.5 (add cross reference to SDG assessment)	see SR1.5
System integration	+	+	+	NE
Role of context	By using the synergies within and between sectors, Energy System Integration aims to increase flexibility in the energy system, maximize the integration of renewable energy and distributed generation, and reduce environmental impact.	Potential of reducing NOx by optimal use of ammonia	ESI aims to increase flexibility in the energy system such as the link between electricity-water nexus, which can optimize the quantity of water	
Line of sight	Combini et al., (2020)	Strbac, (2018)	NREL, (2014)	

1

	Technological		
	Simplicity	Technological scalability	Maturity and technology readiness
Solar energy	+	+	+
Role of context	Globally simple	Globally scalable	Globally mature
Line of sight	Malhotra, A., and T. S. Schmidt, 2020: Accelerating Low-Carbon Innovation. Joule, 4, 1–9, https://doi.org/10.1016/j.joule.2020.09.004.	Haegel, N. M., and Coauthors, 2019: Terawatt-scale photovoltaics: Transform global energy. Science (80-.)., https://doi.org/10.1126/science.aaw1845.	Green, M. A., 2016: Commercial progress and challenges for photovoltaics. Nat. Energy, https://doi.org/10.1038/nenergy.2015.15.
Wind energy	+	±	+
Role of context		Technology is ready, but some materials might be more difficult to obtain or become more expensive	Globally mature
Line of sight	Rohrig, K., and Coauthors, 2019: Powering the 21st century by wind energy—Options, facts, figures. Appl. Phys. Rev., 6, 031303, https://doi.org/10.1063/1.5089877.	IRENA (2019), The fu ure of wind	IRENA (2019), The future of wind
Hydroelectric power	+	+	+
Role of context		Globally scalable	Very matured
Line of sight	IRENA (2021) IHA, 2019: Hydropower Sector Climate Resilience Guide. 75 pp. www.hydropower.org.	IRENA (2021), Renewable Power Generation Costs in 2020, International Ren wable Energy Agency, Abu Dhabi.	IRENA (2021); Killingtveit (2020)
Nuclear	-	±	+
Role of context	Technology is complex but mature (commercial scalability as of 1960).	Qualified and skilled labour force could be an issue in some countries in case of rapid expansion in nuclear new builds Improvements in construction management practices and supply chain are needed in some countries.	Technology is mature. Increased scalability would further improve technology readiness of more advanced reactors.
Line of sight	Massachusetts Institute of Technology, 2018: The Future of Nuclear Energy in a Carbon-Constrained World, An Interdisciplinary MIT Study, MIT, Cambridge	Massachusetts Institute of Technology, 2018: The Future of Nuclear Energy in a Carbon-Constrained World, An Interdisciplinary MIT Study, MIT, Cambridge	OECD NUCLEAR ENERGY AGENCY, 2020: Unlocking Reductions in the Construction Costs of Nuclear: A Practical Guide for Stakeholders, OECD Publishing, Paris.
Carbon Dioxide Capture, Utilization, and Storage	-	±	-
Role of context	Logistically challenging requiring widespread infrastructural coordination	Technology development occurring but at slow rate	Low readiness in several supply chain components

Line of sight	Middleton, R. S., & Yaw, S. (2018). The cost of getting CCS wrong: Uncertainty, infrastructure design, and stranded CO_2. International Journal of Greenhouse Gas Control, 70, 1-11.	Tapia, J. F. D., Lee, J. Y., Ooi, R. E., Foo, D. C., & Tan, R. R. (2018). A review of optimization and decision-making models for the planning of CO_2 capture, utilization and storage (CCUS) systems. Sustainable Production and Consumption, 13, 1-15.	Van der Spek, M., Fout, T., Garcia, M., Kuncheekanna, V. N., Matuszewski, M., McCoy, S., ... & Rubin, E. S. (2020). Uncertainty analysis in the techno-economic assessment of CO_2 capture and storage technologies. Critical review and guidelines for use. International Journal of Greenhouse Gas Control, 100, 103113.
Bioenergy	-	±	±
Role of context	Logistically challenging requiring widespread infrastructural coordination	While traditional biomass and first-generation biofuels are widely used today their scalability is limit d by resource constraints. Scale-up of bioenergy us for other feedstocks will require advanced technologies such as gasification, Fischer-Tropsch processing, hydrothermal liquefaction (HTL), and pyrolysis. and sc ling up these proc sses will require robust business strategies and optimized use of co-products. Several technological and institutional barriers exist for large-scale BECCS implementation	Electricity generated from biomass contributes about 3% of global generation. Tens of billions of gallons of first-generation biofuels are produced per year. Advanced bioenergy pathways could deliver several final energy carriers starting from multiple feedstocks, and many of these pathways can potentially provide CDR. However, while potentially cost-competitive in the future, there are mostly not cost-competitive yet.
Line of sight	Shu, K., Schneider, U. A., & Scheffran, J. (2017). Optimizing the bioenergy industry infrastructure: transportation networks and bioenergy plant locations. Applied Energy, 192, 247-261.	Lee, R.A. and Lavoie, J.M., (2013). From first-to third-generation biofuels: Challenges of producing a commodity from a biomass of increasing complexity. Animal Frontiers, 3(2), pp.6-11.	Baker et al., (2020) Daioglou, V., Rose, S.K., Bauer, N., Kitous, A., Muratori, M., Sano, F., Fujimori, S., Gidden, M.J., Kato, E., Keramidas, K. and Klein, D., (2020). Bioenergy technologies in long-run climate change mitigation: results from the EMF-33 study. *Climatic Change*, *163*(3), pp.1603-1620.
Fossil fuel phaseout	±	±	+
Role of context	Uncertain. Depends on replacement technologies	Uncertain Depends on replacement technologies	Several regions have already demonstrated coal phaseout already
Line of sight	Jakob, M., Steckel, J. C., Jotzo F., Sovacool, B. K., Cornelsen, L., Chandra, R., & Robins, N. (2020). The future of coal in a carbon-constrained climate. Nature Climate Change, 10(8), 704 707.		Keles, D., & Yilmaz, H. Ü. (2020). Decarbonization through coal phase-out in Germany and Europe—Impact on Emissions, electricity prices and power production. Energy Policy, 141, 111472.
Geothermal	+	+	+
Role of context	Globally simple	Globally scalable but need to look beyond electrical use only and support end-use sectors such as heating in industry, agriculture, buildings	Mature but potential for improvement particularly for high depth potential
Line of sight		IRENA, (2018)	Limberger et al (2018)
Energy storage for low-carbon grids	±	+	±

Role of context	Some storage technologies are still in early stage of development and need further development in order to be widely employed.	Different technologies in different sizes are available. Most ES technologies have large- and small-scale options; some are specifically modular, or have built-in flexibility of scale.	Some technologies are still in early stage of development and need further attention to be widely deployed. Some are very mature.
Line of sight	Belderbos, (2019), Shaqsi et al., (2020)	Shaqsi et al., (2020)	Belderbos, (2019), Shaqsi et al., (2020)
Demand side mitigation	+	+	+
Role of context	Most demand options do not rely on complex technology	Most demand options do not rely on technological innovations, and many technologies are scalable, but differs across regions	Some demand options rely on technological innovations, of which some are at low TRL, but many demand options do not rely on technology
Line of sight	see section 6.4.6	see section 6.4.6	see section 6.4.6
System integration	-	+	±
Role of context	Apart from meters, hardware, and simulation platforms, different incentives, decision-making processes, and access to capital due to location or scale need to result in very different energy systems and approaches to energy system integration	From distribution leve to transmission level is scalable	Currently developments in renewable energy, energy storage, and power electronic technologies have been experienced. However, also gaps have been identified: improving decision support tools and their data requirements; smart strategies for resource on demand implementation including energy storage; real time knowledge of parameters; common data repositories; optimization and control structures to integrate energy systems; improved design, installation and control.
Line of sight	O'Malley et al.,(2016)	(EC 2019)	ESFRI, (2018) Ruth, (2014)

	Economic	
	Costs in 2030 and long term	Employment effects and economic growth
Solar Energy	+	+
Role of context	Low and declining	Globally beneficial
Line of sight	Haegel, N. M., and Coauthors, 2019: Terawatt-scale photovoltaics: Transform global energy Science (80-.) , https://doi.org/10.1126/science.aaw1845.	Siegmeier, J., L. Mattauch, M. Franks, D. Klenert, A. Schultes and O. Edenhofer (2017). "The fiscal benefits of stringent climate change mitigation: an overview." Climate Policy: 1-16.
Wind energy	+	+
Role of context	Declining	Globally beneficial

Line of sight	IRENA (2021); Moran et al. 2018	Sandeep Pai, Johannes Emmerling, Laurent Drouet, Hisham Zerriffi, Jessica Jewell, Meeting well-below 2°C target would increase energy sector jobs globally, One Earth, Volume 4, Issue 7, 2021, Pages 1026-1036, ISSN 2590-3322, https://doi.org/10.1016/j.oneear.2021.06.005
Hydroelectric power	±	+
Role of context	Highly project specific and the cost could increase as well. For example, exploitation of sites with more challenging civil engineering conditions may result in higher costs	Beneficial
Line of sight	IRENA (2021); Moran et al. 2018	Sadoff C W., Hall, J.W., Grey, D., Aerts, J.C.J.H., Ait-Kadi, M., Brown, C., Cox, A., Dadson, S., Garrick, D., Kelman, J., McCornick, P., Ringler, C., Rosegrant, M., Whittington, D. and Wiberg, D (2015) Securing Water, Sustaining Growth: Report of the GWP/OECD Task Force on Water Security and Sustainable Growth, University of Oxford, UK, 180pp.
Nuclear	±	±
Role of context	Costs for new builds are project/country/region specific. In some coun ries it is competitive, in others less. Life time extensions are much cheaper than new builds.	Feedbacks on the economies are positive in some countries. Employment effects are more pronounced during the construction phase.
Line of sight	OECD INTERNATIONAL ENERGY AGENCY, NUCLEAR ENERGY AGENCY, Projected Costs of Generating Electricity: 2020 Edition, OECD Publishing, Paris (2020). OECD NUCLEAR ENERGY AGENCY, 2020: Unlocking Reductions in he Construction Costs of Nuclear: A Practical Guide for Stakeholders, OECD Publishing, Paris.	OECD NUCLEAR ENERGY AGENCY, 2019, Measuring Employment Generated by the Nuclear Power Sector, OECD publishing. Paris. Lee, M.K. et al. (2009), "Contribution of nuclear power to the national economic development in Korea", Nuclear Engineering and Technology, Vol. 41(4).
Carbon Dioxide Capture, Utilization, and Storage	±	+
Role of context	Costs are uncertain though decline is projected with learning	Potential increase in employment in several allied sectors
Line of sight	van der Spek, M., Rous analy, S., & Rubin, E. S. (2019). Best practices and recent advances in CCS cost engineering and economic analysis. International Journal of Greenhouse Gas Control, 83, 91-104.	Tvinnereim, E., & Ivarsflaten, E. (2016). Fossil fuels, employment, and support for climate policies. Energy Policy, 96, 364-371.
Bioenergy	±	+
Role of context	Technology costs of advanced bioenergy pathways are higher compared to alternatives today and while hey are generally anticipated to reduce high uncertain y exist about future costs	Potential increase in employment if bioenergy use increases
Line of sight	Daioglou, V., Rose, S K., Bauer, N., Kitous, A., Muratori, M., Sano, F., ... & Klein, D. (2020) Bio nergy technologies in long-run climate change mitigation: results from the EMF-33 study. Climatic Change, 1-18.	Ram, M., Aghahosseini, A. and Breyer, C., 2020. Job creation during the global energy transition towards 100% renewable power system by 2050. Technological Forecasting and Social Change, 151, p.119682.

Fossil fuel phaseout	±	±
Role of context	Overall impacts are positive when environmental externalities are considered. However, there could be large stranded assets	Low-carbon sources demonstrate good employment avenues. However, regional inequity may be present causing unemployment of fossil fuel sector workers
Line of sight	Wang, C., Zhang, L., Zhou, P., Chang, Y., Zhou, D., Pang, M., & Yin, H. (2019). Assessing the environmental externalities for biomass-and coal-fired electricity generation in China: A supply chain perspective. Journal of environmental management, 246, 758-767.	He, G., Lin, J., Zhang, Y., Zhang, W., Larangeira, G., Zhang, C., ... & Yang, F. (2020). Enabling a rapid and just transition away from coal in China. One Earth, 3(2), 187-194.
Geothermal	+	-
Role of context	Potential for reduction for high depth potential thanks to technology progress in drilling. Typical costs for geothermal power plants USD 1 870 to USD 5 050/ kW depending on size and technology. Potential for LOCE reduction in the long-term. USD 0.04-0.14 to 0.037 to 0.11 by 2050	Little impact on employment and economic growth. High capital cost per unit
Line of sight	a-IRENA (International Renewable Energy Agency "Renewable Cost Database", IRENA, http:/ costing.irena.org/irena-costing.aspx.IRENA (2017); b-IRENA (2017), Geothermal Power: Technology Brief; c- https://www.energy.gov/eere/geothermal/geothermal-faqs	
Energy storage for low-carbon grids	+	+
Role of context	Various energy storage technologies also differ in their cost (capital, running and maintenance, labor, and replacement after some intervals) Although there is some prediction in the literature, however there is uncertainty and perfect insight is not possible.	Skilled employment in manufacturing, maintenance and installation companies.
Line of sight	Shaqsi et al., (2020)	Ram et al., (2020)
Demand side mitigation	+	±
Role of context	Some low demand options have high upfront costs while many options would save money;	Depends on option; market shares of some technologies and products may decrease, while others increase. Energy efficiency and energy transition has a positive impact on employment,
Line of sight	DOI 10.1007/s41825-017-0004-5; SR1.5 https://www.tandfonline.com/doi/full/10.1080/09535314.2019.1695584; https://ec.europa.eu/energy sites ener/files/documents/CE_EE_Jobs_main%2018Nov2015.pdf ; https://www.ilo.org/weso-greening/documents/WESO Greening EN chap2 web.pdf	
System integration	+	+
Role of context	The amount f cost reduction has been reported in the reference.	The cost reduction leads to economic growth through providing opportunity to invest in other fields. Furthermore, developing renewable energies can increase employment rate, ; https://www.ilo.org/weso-greening/documents/WESO_Greening_EN_chap2_web.pdf
Line of sight	Combini et al., (2020)	Combini et al., (2020)

	Socio-cultural		
	Public acceptance	Effects on health and wellbeing	Distributional effects
Solar energy	+	+	±
Role of context	high upfront costs and long payback periods may be barriers for adoption; not feasible for all households (e.g., apartments, rental houses)	Globally beneficial	High upfront costs deter adoption for low-income groups and in developing countries, despite low total costs. Distribution of costs and benefits change as a function of design choices.
Line of sight	Bessette & Arvai, 2018; Boudet, 2019; Faiers & Neame, 2006; Hanger et al, 2016; Hazboun & Boudet, 2020; Jobin & Siegrist, 2018; Korcaj et al., 2015; Ma et al., 2015; Mcgowan & Sauter, 2005; Palm, 2017; Steg, 2018; Vasseur & Kemp, 2015; Whitmarsh et al., 2011	Shindell, D., G. Faluvegi, K. Seltzer nd C. Shindell (2018). "Quantified, localized health benefits of accelerated carbon dioxide emissions reductions." Nature Climate Ch nge: 1.	McCauley, D., V. Ramasar, R. J. Heffron, B. K. Sovacool, D. Mebratu and L. Mundaca (2019). "Energy justice in the transition to low carbon energy systems: Exploring key themes in interdisciplinary research." Applied Energy 233-234: 916-921.
Wind energy	±	±	±
Role of context	Higher acceptance for offshore wind projects; local wind projects might evoke resistance	Generally positive impact as climate change decreases, but noise and aesthetic issu s at some pl ces.	The growing debate around the environmental justice of large wind farms because of land pressures and uneven development. This could be a barrier if it is considered in each project
Line of sight	Ipsos, (2010); Rand & Hoen, (2017); Devine-Wright, (2005); Bates & Firestone, (2015); Hoen et al. (2019); Steg, (2018)	Delicado et al, (2016)	Ávila, (2018); Liljenfeldt & Pettersson, (2017); Liebe et al, (2017)
Hydroelectric power	±	±	-
Role of context	New large hydropower is controvers al in som areas if local residents and ecosystems re endangered and trust in government or companies is low, but the technology is generally well-accepted in many regions.	Both positive (reduce climate change) and negative (can have negative health impacts).	Large hydropower could have negative impacts on livelihoods, so affecting distributional and equity aspects

Line of sight	Steg 2018; Mccartney 2009; Gormally et al. (2014); Plum et al. (2019); Rudolf et al. (2014); Boyd et al. (2019); Karlstrøm and Ryghaug (2014); Hazboun and Boudet (2020); Bronfman et al. (2015); Vince (2010); Kaldellis et al. (2013); Boyd et al., 2019; Bronfman et al., 2012, 2015; Ek, 2005; Gormally et al., 2014; Hazboun & Boudet, 2020; Kaldellis et al., 2013; Karlstrøm & Ryghaus, 2014; Plum et al., 2019; Rudolf et al., 2014; Steg, 2018; Vince, 2010 M. Kapsali, E. Kaldelli, and E. Katsanou, 2013: Comparing recent views of public attitude on wind energy, photovoltaic and small hydro applications. Renew. Energy, 52, 197–208, https://doi.org/10.1016/j.renene.2012.10.045.	Leonard B Lerer, Thayer Scudder (1999). Health impacts of large dams, Environmental Impact Assessment Review, Volume 19, Issue 2, Pages 113-123, https://doi.org/10.1016/S0195-9255(98)00041-9. https://pubs.acs.org/doi/pdf/10.1021/acs.est.6b04447 https://www.sciencedirect.com/science/article/pii/S2212096321000097	Siciliano & Urban, 2017; Gunawardena, 2010; Obour et al, 2016; Nguyen et al, 2017; Owusu et al, 2019; Lebel et al 2019
Nuclear	±	±	±
Role of context	In some countries public acceptance is low, in others it is higher. Depends on perceived risks and benefits for economy, climate change mitigation and energy security	The overall impacts on human health from the normal operation of nuclear power plants are low. Yet, serious health impacts in case of nuclear accidents	The need to isolate high-level radioactive waste from the biosphere for millennia might raise concerns about intergenerational equity.
Line of sight	Bird et al., 2014; Bolsen & Cook, 2008; Corner et al, 2011; Gupta et al., 2019; Hobman & Ashworth, 2013; Jobin et al., 2019; Pampel, 2011; Poortinga et al., 2013; Siegrist & Visschers 2013; Soni, 2018; Tsujikawa et al., 2016; Steg, 2018	Hirschberg S. et al., 2016: Health effects of technologies for power generation: contributions from normal operation, severe accidents and terrorist threat. Reliab. Eng. Syst. Saf. 145, 373–387; TREYER, K., et al., 2014: Human health impacts in the life cycle of future European electricity generation, Energy Policy 74 Suppl. 1 S31–S44. https://pubmed ncbi nlm nih.gov/34436103/ https://www.epa.gov/radiation/radiation-health-effects https://www.thelancet.com/journals/lancet/article/PIIS0140-6736(15)61106-0/fulltext	BROWN, D.A., "Comparative ethical issues entailed in the geological disposal of radioactive waste and carbon dioxide in the light of climate change", Geological Disposal of Carbon Dioxide and Radioactive Waste: A Comparative Assessment (TOTH, F.L., Ed.), Springer, Dordrecht (2011) 317–337; INTERNATIONAL ATOMIC ENERGY AGENCY, Nuclear Technology and Economic Development in the Republic of Korea, Information Booklet, IAEA, Vienna (2009).

			INTERNATIONAL ATOMIC ENERGY AGENCY, Nuclear Power and Sustainable Development (2016)
Carbon Dioxide Capture, Utilization, and Storage	-	±	±
Role of context	Many people are unfamiliar with CCS, so have not formed firm opinions. Some firmly reject CCS; some are concerned that CCS may avoid that GHG emission reductions take place	Positive impacts on health due to reductions in climate change, but also negative impacts due to increase or no change in air pollution due to fossil energy use	On the one, protects future generation against negative impacts of climate change, on the other hand a lot of uncertainty about the technology for future generations
Line of sight	Brown, D.A., "Comparative ethical issues entailed in the geological disposal of radioactive waste and carbon dioxide in the light of climate change", Geological Disposal of Carbon Dioxide and Radioactive Waste: A Comparative Assessment (TOTH, F L., Ed), Springer, Dordrecht (2011) 317–337; Science for Environment Policy: European Commission DG Environment News Alert Service, edited by SCU, The University of the West of England, Bristol. Jacobsen (2019). The Health and Climate Impacts of Carbon Capture and Direct Air Capture. Energy & Environmental Science 12(12). DOI: 10.1039/C9EE02709B		
Bioenergy	-	±	±
Role of context	Acceptability of bioenergy is relatively low compared to other renewable energy sources like solar and wind. Usually bioenergy from waste products (e.g., food waste) is seen more favorably than from purposely-grown energy crops, which are more controversial.	Bioenergy use (without CCS at the final point of use) impacts air quality and large-scale adoption raises a broad set of sustainability concerns.	Labour conditions could determine impacts on poverty and equity. Bioenergy offers an opportunity to replace displaced fossil fuel jobs and impact global trade. Costs and benefits of bioenergy could be unevenly distributed.
Line of sight	Poortinga, W., Aoyagi, M. and Pidgeon, N F., 2013. Public perceptions of climate change and energy futures before and after the Fukushima accident: A comparison between Britain and Japan Energy Policy, 62, pp.1204-1211. Demski, C., Butler, C., Parkhill, K.A., Spence, A. and Pidgeon, N.F., 2015 Public values for energy system change. Global Environmental Change 34 pp.59-69. Haikola, S., Hansson, A., & Anshelm, J (2019). From polarization to reluctant acceptance–bioenergy with carbon capture and storage (BECCS) and the post-normalization of the climate debate. Journal of Integrative Environmental Sciences, 16(1), 45-69.	Hess, P , Johnston, M., Brown-Steiner, B., Holloway, T., de Andrade, J.B. and Artaxo, P., 2009. Air quality issues associated with biofuel production and use. Cornell University Library's Initiatives in Publishing (CIP) Scovronick M. and Wilkonson P. (2014). Health impacts of liquid biofuel production and use: A review. Global Environmental Change 24, 155-164. doi.org/10.1016/j.gloenvcha.2013.09.011	Ram, M., Aghahosseini, A. and Breyer, C., 2020. Job creation during the global energy transition towards 100% renewable power system by 2050. Technological Forecasting and Social Change, 151, p.119682. Muratori, M., Calvin, K., Wise, M., Kyle, P. and Edmonds, J., 2016. Global economic consequences of deploying bioenergy with carbon capture and storage (BECCS). Environmental Research Letters, 11(9), p.095004. Daioglou, V., Muratori, M., Lamers, P., Fujimori, S., Kitous, A., Köberle, A.C., Bauer, N., Junginger, M., Kato, E., Leblanc, F. and Mima, S., 2020. Implications of climate change mitigation strategies on

			international bioenergy trade. Climatic Change, 163(3), pp.1639-1658.
Fossil fuel phaseout	+	+	+
Role of context	Natural gas is evaluated somewhat more favorably than coal and oil; acceptability of fossil energy higher in countries that strongly rely on them		
Line of sight	Cutler, D. & F. Dominici. 2018. A Breath of Bad Air: Cost of the Trump Environmental Agenda May Lead to 80 000 Extra Deaths per Decade. *JAMA*. 319(22):2261-2262. doi:10.1001/jama.2018.7351. Lelieveld et al. 2019. Effects of fossil fuel and total anthropogenic emission removal on public health and climate. *PNAS*, 116 (15), 7192-7197 Nansai, K., Tohno, S., Chatani, S. *et al.* Consumption in the G20 nations causes particulate air pollution resulting in two million premature deaths annually. *Nat Commun* 12, 6286 (2021). https://doi.org/10.1038/s41467-021-26348-y Mikati et al. (2018). Disparities in Distribution of Particulate Matter Emission Sources by Race and Poverty Status. *American Journal of Public Health,* 108:480-485 Zhang et al. (2018). Long-term trends in the ambient PM2.5 and O3-related mortality burdens in the United States under emission reductions from 1990 to 2010. *Atmos. Chem. Phys*, 18:1–14.		
Geothermal	±	-	±
Role of context	Perceived as relatively environmentally-friendly but concerns about water scarcity, noise, smell, seismic risks of drilling, and landscape damage.	Water quality in the area may be affected. Noise pollution	The impacts on income poverty and inequality may be dependent of resource lifespan. Improving standards of living, energy access and water access
Line of sight	Hazboun & Boudet, (2020); Karytsas, Polyzou, & Karytsas, (2019); Pellizzone, Allansdottir, De Franco, Muttoni, & Manzella, (2015); Steel, Pierce, Warner, & Lovrich, (2015); Dowd, Boughen, Ashworth, & Carr-Cornish, (2011); Walker, 1995; Tampakis, Tsantopoulos, Arabatzis, & Rerras, (2013).	Shortall et al., (2015)	Shortall et al., (2015)
Energy storage for low-carbon grids	±	+	±

Role of context	Awareness of storage technologies is low, and limited evidence varies across technologies; hydrogen is perceived to have advantages (clean, offers energy storage) and disadvantages (safety concerns). Batteries are evaluated slightly positively, but are believed to be expensive, somewhat unsafe, and people are concerned about recycling options; for EV batteries, people are concerned about cars not being fully loaded when needed ("range anxiety"). Very important to address safety concerns now, as just a few high-profile accidents can damage the technology's reputation.	In addition to emission reductions, energy storage is also vital for essential service providers like healthcare sector which rely mainly upon energy storage. Safety issues for workers in material extraction, processing and component manufacture for some technologies. No issues at point of use, under normal operation, as long as hydrogen and battery safety is controlled.	High upfront costs deter adoption in developing countries, despite low costs. Distribution of costs and benefits change as a function of design choices. Global supply chain issues with some materials, which could be solved through local recycling.
Line of sight	Acola, (2017); Agnew & Dargusch, (2017); Abrosio-Albala et al., (2020); Emmerich et al., (2020); Michaels & Parag, (2016); Steffen, (2012); Thomas et al., (2019); Zaunbrecher et al., (2016)		
Demand side mitigation	±	+	+
Role of context	Acceptance is higher for options that do not require significant changes in lifestyles. Acceptance will be higher when financial, legal and infrastructural barriers for demand side mitigation are removed.		Energy savings save money and improves equity and reduce poverty, but some options are associated with high costs that can increase inequality. Access to modern energy can reduce poverty
Line of sight	https://www.iea.org/reports/multiple-benefits-of-energy-effi iency/health-and-wellbeing https://www.epa.gov/sites/default/files/2018-07/documents/mbg_2-4_em ssionshealthbenefits.pdf https://www.cambridge.org/core/journals/journal-of-benefit-cost analysis/article/differential-and-distributional-effects-of-energy-efficiency-surveys-evidence-from-electricity-consumption/543329FFEDB0B2E433BF3D6F2F8E3BD5 https://www.sciencedirect.com/science/article/pii/S1364032115001471 https://www.tandfonline.com/doi/abs/10.1080/14786451.2020.1815744?journalCode=gsol20		
System integration	±	+	LE
Role of context	Most evidence on different aspec s of system integration, not system as a whole. Public acceptance will be higher when investments costs are removed and privacy i sues are addressed. Extending transmission lines is generally evaluated negatively. Energy independence and b ing self-sufficient positively evaluated	Reducing air pollution prevents some diseases	
Line of sight	Leijten e al , (2014); Lienert e al. (2015); Michaels & Parag, (2016); Spence et al., (2015)		

Institutional

	Political acceptance	Institutional capacity, governance, cross-sectoral coordination	Legal and administrative capacity
Solar energy	±	+	+
Role of context	Opposed by fossil interests	Need support for rapid scale up in developing countries	Electricity market reforms required
Line of sight	Stokes, L. C. and H. L. Breetz (2018). "Politics in the U.S. energy transition: Case studies of solar, wind, biofuels and electric vehicles policy." Energy Policy 113(Supplement C): 76-86.	Creutzig, F., P. Agoston, J. C. Goldschmidt, G. Luderer, G. Nemet and R. C. Pietzcker (2017). "The underestimated potential of solar energy to mitigate climate change." Nature Energy 2: nenergy2017140.	Das, S., E. Hittinger and E. Williams (2020). "Learning is not enough: Diminishing marginal revenues and increasing abatement costs of wind and solar." Renewable Energy 156: 634-644.
Wind energy	±	±	-
Role of context	Opposed by fossil interests	Need support for rapid scale up of electricity transmission	Electricity market reforms required; also reforms in the project assessment regulations
Line of sight	Stokes, L. C. and H. L. Breetz (2018). "Politics in the U.S. energy transition: Case studies of solar, wind, biofuels and electric vehicles policy." Energy Policy 113(Supplement C): 76-86.	IRENA (2019), The future of wind	Das, S., E. Hittinger and E. Williams (2020). "Learning is not enough: Diminishing marginal revenues and increasing abatement costs of wind and solar." Renewable Energy 156: 634-644.
Hydroelectric power	±	±	±
Role of context	large reservoirs are becoming less politically accepted especially in developed nations due to environmental issues,	challenges could arise due to competition in water use (managing multipurpose reservoirs)	water rights, water markets in some regions
Line of sight	Killingtveit (2020)	OECD (2015 , OECD Principles on Water Governance, www.oecd.org governance/oecd-principles-onwater-gov rnance htm; OECD (2011), Water Governance in OECD Countries: A Multi-level Approach, OECD, Publishing, Paris, http://dx.doi.org/10.1787/9789264119284-en. Moran, E. F., M. C. Lopez, N. Moore, N. Müller, and D. W. Hyndman, 2018: Sustainable hydropower in the 21st century. Proc. Natl. Acad. Sci., 115, 11891 LP – 11898, https://doi.org/10.1073/pnas.1809426115.	Ito, S., S. Khatib, and M. Nakayama, 2015: Conflict over a hydropower plant project between Tajikistan and Uzbekistan. Int. J. Water Resour. Dev., 32, 1–16, https://doi.org/10.1080/07900627.2015.1076381.
Nuclear	±	-	±

Role of context	Similar as to public acceptance, political support in some countries is low while in others is high	Lengthy license process, varying political conditions and support, regulatory regimes, complex financial framework.	It differs across countries, whether a country already has a nuclear power or whether it is a newcomer country. In the latter case, a wide range of infrastructure issues needs to be addressed, including facilities and equipment, as well as human and financial resources, and the legal and regulatory framework.
Line of sight	OECD NUCLEAR ENERGY AGENCY, 2020: Unlocking Reductions in the Construction Costs of Nuclear: A Practical Guide for Stakeholders, OECD Publishing, Paris.	Massachusetts Institute of Technology, 2018: The Future of Nuclear Energy in a Carbon-Constrained World, An Interdisciplinary MIT Study, MIT, Cambridge.	Massachusetts Institute of Technology, 2018: The Future of Nuclear Energy in a Carbon-Constrained World, An Interdisciplinary MIT Study, MIT, Cambridge.
Carbon Dioxide Capture, Utilization, and Storage	±	+	±
Role of context	Varies across countries	Several new schemes globally incentivize CCUS sufficiently	Need for robust monitoring and verification
Line of sight	Xenias, D., & Whitmarsh, L. (2018). Carbon capture and storage (CCS) experts' attitudes to and experience with public engagement. International Journal of Greenhouse Gas Control, 78, 103-116.	Esposito, R. A., Kuuskraa, V. A., Rossman, C. G., & Corser, M. M. (2019). Reconsidering CCS in the US fossil-fuel fired electricity industry under section 45Q tax credits. Greenhouse Gases Scien e and Techn logy 9(6), 1288-1301.	n
Bioenergy	±	-	±
Role of context	Many bioenergy markets depend on energy policy support for bioenergy which varies for different countries.	Bioenergy complexities require specific governance and major cross-sectoral coordination	Assessing bioenergy impacts and long-term effects is complicated and even more difficult it is gauging actual carbon removal for BECCS applications
Line of sight	Roos, A., Graham, R.L., Hektor, B. and Rakos, C., 1999. Critical factors to bioenergy implementation. Biomass and Bioenergy, 17(2) pp.113-126.	Alsaleh M., Abdul-Rahim, A.S. and Abdulwakil, M.M., 2021. The importanc of worldwide governance indicators for transitions toward sustainable bioenergy industry. Journal of Environmental Management, 294, p.112960. Fridahl, M., & Lehtveer, M. (2018). Bioenergy with carbon capture and storage (BECCS): Global potential, investment preferences, and deployment barriers. Energy Research & Social Science, 42, 155-165.	Torvanger, A. (2019). Governance of bioenergy with carbon capture and storage (BECCS): accounting, rewarding, and the Paris agreement. Climate Policy, 19(3), 329-341.
Fossil fuel phaseout	+	±	-
Role of context	Several governments are indicating support for coal phaseout such as PPCA	It would require change in fossil fuel subsidy mechanisms	Susceptible to leakage and other effects

Line of sight	Jewell, J., Vinichenko, V., Nacke, L., & Cherp, A. (2019). Prospects for powering past coal. Nature Climate Change, 9(8), 592-597.	Kalkuhl, M., Steckel, J. C., Montrone, L., Jakob, M., Peters, J., & Edenhofer, O. (2019). Successful coal phase-out requires new models of development. Nature Energy, 4(11), 897-900.	Nielsen, T., Baumert, N., Kander, A., Jiborn, M., & Kulionis, V. (2020). The risk of carbon leakage in global climate agreements. International Environmental Agreements: Politics, Law and Economics, 1-17.
Geothermal	+	+	NE
Role of context	Rather positive by and large.	Some countries are providing policy support in the form risk guarantees, investment grant to mitigate uncertain drilling operation outcomes and high up-front costs	
Line of sight	Karytsas et al. 2019	IEA, renewables 2019	
Energy storage for low-carbon grids	+	±	±
Role of context	General political acceptance and active promotion in the US, UK and Europe.	Given concerns expressed about the competency of some communities and local authorities, there may well be a space for community, local government and private sector organizations to develop partnerships to deliver energy services in new, more flexible ways. It is not clear how such hybrid relationships may coevolve with storage and other flexibility technologies over the longer term. Work required on these markets	The UK and Europe are exploring how to overcome these barriers and have been largely successful.
Line of sight	Imperial, Poyry, (2017)/ European energy innovation, (2020)	Thomas et al., (2019)	European energy innovation, (2020)
Demand side mitigation	±	+	+
Role of context	Varies across mitigation options, less acceptable when options face public resistance;	Many options rely on voluntarily change so no governance issues and institutional barriers. Transition to distributed energy system faces institutional barriers and requires novel institutional arrangement	Some options need legal and administrative support, such as distributed energy systems
Line of sight	https://doi.org/10.1016/j.rser.2020.109841; DOI:10.1016/j.erss.2017.03.013		
System integration	+	+	±
Role of context	Government should provide incentives (e.g., a government can invest in high-voltage transmission, while individuals will not). It is needed to align the market design with low carbon agenda. System integration can provide evidence in this regard.	Government should provide incentives (e.g., a government can invest in high-voltage transmission, while individuals will not). It is needed to align the market design with low carbon agenda. System integration can provide evidence in this regard.	Government should provide incentives (e.g., a government can invest in high-voltage transmission, while individuals will not). It is needed to align the market design with low carbon agenda. System integration can provide evidence in this regard.
Line of sight	Imperial, Poyry, (2017)	Imperial, Poyry, (2017)	Imperial, Poyry, (2017)

			van Soest (2019). Peer-to-peer electricity trading: A review of the legal context. https://doi.org/10.1177/1783591719834902