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Energy Systems
Supplementary Material

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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 II.11 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, doi:10.1016/j.apenergy.2019.113968.	IEA, 2020: Clean energy progress after the Covid-19 crisis will need reliable supplies of critical minerals. International Energy Agency (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(8)**, e0236958, doi: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, R. et al., 2022: High resolution large-scale onshore wind energy assessments: A review of potential definitions, methodologies and future research needs. *Renew. Energy*, **182**, 659–684, doi:10.1016/j.renene.2021.10.027.	Rohrig, K. et al., 2019: Powering the 21st century by wind energy—Options, facts, figures. *Appl. Phys. Rev.*, **6(3)**, 031303, doi:10.1063/1.5089877.	Tröndle, T., 2020: Supply-side options to reduce land requirements of fully renewable electricity in Europe. *PLoS One*, **15(8)**, e0236958, doi: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, T., M. Kumar, R.K. Mall, and R.S. Singh, 2017: Airing 'clean air' in Clean India Mission. *Environ. Sci. Pollut. Res.*, **24**, 6399–6413, https://doi.org/10.1007/s11356-016-8264-y. 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(2)**, e0171844, doi:10.1371/journal.pone.0171844. Van Vliet et al., 2016. van Vliet, M.T.H., J. Sheffield, D. Wiberg, and E.F. Wood, 2016a: Impacts of recent drought and warm years on water resources and electricity supply worldwide. *Environ. Res. Lett.*, **11(12)**, doi:10.1088/1748-9326/11/12/124021. Zhou, Y. et al., 2015: A comprehensive view of global potential for hydro-generated electricity. *Energy Environ. Sci.*, **8(9)**, 2622–2633, doi:10.1039/C5EE00888C.	Lu, S., W. Dai, Y. Tang, and M. Guo, 2020: A review of the impact of hydropower reservoirs on global climate change. *Sci. Total Environ.*, **711**, 134996, doi:10.1016/j.scitotenv.2019.134996. Tremblay, A., L. Varfalvy, M. Garneau, and C. Roehm, 2005: *Greenhouse gas Emissions-Fluxes and Processes: hydroelectric reservoirs and natural environments*. Springer Science & Business Media, Berlin, Heidelberg. Jacobson, M.Z. and M.A. Delucchi, 2011: Providing all global energy with wind, water, and solar power, Part I: Technologies, energy resources, quantities and areas of infrastructure, and materials. *Energy Policy*, **39(3)**, 1154–1169, doi:10.1016/j.enpol.2010.11.040.	Ioannidis, R. and D. Koutsoyiannis, 2020: A review of land use, visibility and public perception of renewable energy in the context of landscape impact. *Appl. Energy*, **276**, 115367, doi:10.1016/j.apenergy.2020.115367. Trainor, A.M., R.I. McDonald, and J. Fargione, 2016: Energy Sprawl is the Largest Driver of Land Use Change in United States. *PLoS One*, **11(9)**, e0162269–e0162269, doi:10.1371/journal.pone.0162269.

Notes:

– The indicator has a negative impact on the feasibility of the option

± The indicator has mixed positive and negative impacts on the feasibility of the option

+ The indicator has a positive impact on the feasibility of the option

0 The indicator does not affect the feasibility of the option

NA The indicator is not applicable for the option

NE no evidence available to assess the impact of the indicator on the feasibility of the option

LE limited evidence available to assess the impact of the indicator on the feasibility of the option

	Geophysical		
	Physical potential	**Geophysical resources**	**Land use**
Nuclear	±	+	+
Role of context	Physical potential is not an issue. Existing sites could be reused, new sites can be identified and only a few countries might face space limitations.	Sufficient resources for deployment at meaningful scales	Has low footprint for land. Some reference 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., S. Hashim, M.S. Aljohani, M.A. Saleh, and N. Xoubi, 2019: Potential areas for nuclear power plants siting in Saudi Arabia: GIS-based multi-criteria decision making analysis. *Prog. Nucl. Energy*, **110**, 110–120, doi:10.1016/j.pnucene.2018.09.018. Zhang, X.Y. et al., 2020: Perspective on Site Selection of Small Modular Reactors. *J. Environ. Informatics Letters.*, **3**, 39-48, doi:10.3808/jeil.202000026.	NEA/IAEA, 2019: *Uranium 2018. Resources, production and demand*. OECD Publishing, Paris, France, 462 pp.	Fthenakis, V. and H.C. Kim, 2009: Land use and electricity generation: A life-cycle analysis. *Renew. Sustain. Energy Rev.*, **13(6–7)**, 1465–1474, doi:10.1016/j.rser.2008.09.017. Luderer, G. et al., 2019: Environmental co-benefits and adverse side-effects of alternative power sector decarbonization strategies. *Nat. Commun.*, **10(1)**, 1–13, doi:10.1038/s41467-019-13067-8. Cheng, V.K.M. and G.P. Hammond, 2017: Life-cycle energy densities and land-take requirements of various power generators: A UK perspective. *J. Energy Inst.*, **90(2)**, 201–213, doi:10.1016/j.joei.2016.02.003.
Carbon dioxide (CO_2) capture, utilisation and storage	±	±	+
Role of context	Limited in some sectors – including CO_2 utilisation, bioenergy with carbon capture and storage (CCS), etc.	Limited in some sectors – including CO_2 utilisation, bioenergy with CCS, etc.	Less than several other mitigation options (not considering bioenergy)
Line of sight	Budinis, S., S. Krevor, N. Mac Dowell, N. Brandon, and A. Hawkes, 2018: An assessment of CCS costs, barriers and potential. *Energy Strateg. Rev.*, **22**, 61–81, doi:10.1016/j.esr.2018.08.003. Selosse, S. and O. Ricci, 2017: Carbon capture and storage: Lessons from a storage potential and localization analysis. *Appl. Energy*, **188**, 32–44, doi:10.1016/j.apenergy.2016.11.117.		
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

	Geophysical		
	Physical potential	Geophysical resources	Land use
Line of sight	Roe, S. et al., 2021: Land-based measures to mitigate climate change: Potential and feasibility by country. *Glob. Change Biol.*, **27(23)**, 6025–6058, doi:10.1111/gcb.15873. Slade, R., A. Bauen, and R. Gross, 2014: Global bioenergy resources. *Nat. Clim. Change*, **4(2)**, 99–105, doi:10.1038/nclimate2097. Fuss, S. et al., 2018: Negative emissions—Part 2: Costs, potentials and side effects. *Environ. Res. Lett.*, **13(6)**, 063002, doi:10.1088/1748-9326/aabf9f.	Hanssen, S.V et al., 2020: Biomass residues as twenty-first century bioenergy feedstock—a comparison of eight integrated assessment models. *Clim. Change*, **163(3)**, 1569–1586, doi:10.1007/s10584-019-02539-x.	Strapasson, A. et al., 2017: On the global limits of bioenergy and land use for climate change mitigation. *GCB Bioenergy*, **9(12)**, 1721–1735, doi:10.1111/gcbb.12456. Smith, P. et al., 2019: Interlinkages Between Desertification, Land Degradation, Food Security and Greenhouse Gas Fluxes: Synergies, Trade-offs and Integrated Response Options. In: *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, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Portner, D.C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK, and New York, NY, USA, pp. 551–672. IPCC, 2019: Summary for Policymakers. In: *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, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D.C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK, and New York, NY, USA.
Fossil fuel phase-out	**NA**	+	±
Role of context	Large physical resource to remain unutilised	Mining and depletion of non-renewable resources would reduce	Uncertain but could be positive if it reduces the need for carbon dioxide removal (CDR)
Line of sight	McGlade, C. and P. Ekins, 2015: The geographical distribution of fossil fuels unused when limiting global warming to 2 °C. *Nature*, **517(7533)**, 187–190, doi:10.1038/nature14016.	Luderer, G. et al., 2019: Environmental co-benefits and adverse side-effects of alternative power sector decarbonization strategies. *Nat. Commun.*, **10(1)**, 1–13, doi:10.1038/s41467-019-13067-8.	Kriegler, E. et al., 2017: Fossil-fueled development (SSP5): An energy and resource intensive scenario for the 21st century. *Glob. Environ. Change*, **42 (sup C)**, 297–315, doi:10.1016/j.gloenvcha.2016.05.015.
Geothermal	–	+	+
Role of context	Large potential but very site specific. Upfront cost particularly high and associated with uncertainties for drilling.	For direct thermal uses, the technical potential is estimated at 10 to 312 EJ yr^{-1} (IPCC 2011). For electricity generation, technical potential is estimated between 118 EJ yr^{-1} (to 3 km depth) and 1109 EJ yr^{-1} (to 10 km depth).	Little impact on land use
Line of sight	IPCC, 2011: Summary for Policymakers. In: *Special Report on Renewable Energy Sources and Climate Change Mitigation* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow, (eds.)]. Cambridge University Press, Cambridge, UK, and New York, NY, USA.	IPCC, 2011: Summary for Policymakers. In: *Special Report on Renewable Energy Sources and Climate Change Mitigation* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow, (eds.)]. Cambridge University Press, Cambridge, UK, and New York, NY, USA.	Trevor M. Hunt, 2001, Institute of Geological and Nuclear Sciences, Taupo, New Zealand, https://orkustofnun.is/gogn/unu-gtp-report/UNU-GTP-2000-01.pdf

	Geophysical		
	Physical potential	**Geophysical resources**	**Land use**
Energy storage for low-carbon grids	–	+	±
Role of context	The size of grid networks, customer demands, storage capacity and location of devices, their advantages and limitations, cost, lifetime, and impacts on the environment must be considered during selection decision. The sources of power production, renewable 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, A. Z. A., Sopian, K., & Al-Hinai, A. (2020). Review of energy storage services, applications, limitations, and benefits. Energy Reports.	EPA (Environmental Protection Agency), 2019. Energy and the environment, electricity storage. Retrieved on December 11, 2019, from https://www.epa.gov/energy/electricity-storage.	Shaqsi, A. Z. A., Sopian, K., & Al-Hinai, A. (2020). Review of energy storage services, applications, limitations, and benefits. Energy Reports. Ozarslan, A. (2012). Large-scale hydrogen energy storage in salt caverns. *International Journal of Hydrogen Energy*, **37(19)**, 14265–14277.
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, B., Garrett, B., Macmillan, S., Rice, B., Komomua, C., O'Malley, M., and Zimmerle, D. (2012). Energy systems integration: a convergence of ideas (No. NREL/TP-6A00-55649). National Renewable Energy Lab.(NREL), Golden, CO (United States).		

	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	Minimal effects in manufacturing	Concerns in protected areas
Line of sight	Mahmud, M., N. Huda, S. Farjana, and C. Lang, 2018: Environmental Impacts of Solar-Photovoltaic and Solar-Thermal Systems with Life-Cycle Assessment. *Energies*, **11(9)**, 2346, doi:10.3390/en11092346.	Heath, G.A. et al., 2020: Research and development priorities for silicon photovoltaic module recycling to support a circular economy. *Nat. Energy*, **5(7)**, 502–510, doi:10.1038/s41560-020-0645-2. Mahmud, M., N. Huda, S. Farjana, and C. Lang, 2018: Environmental Impacts of Solar-Photovoltaic and Solar-Thermal Systems with Life-Cycle Assessment. *Energies*, **11(9)**, 2346, doi:10.3390/en11092346.	Mahmud, M., N. Huda, S. Farjana, and C. Lang, 2018: Environmental Impacts of Solar-Photovoltaic and Solar-Thermal Systems with Life-Cycle Assessment. *Energies*, **11(9)**, 2346, doi: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(44)**, 13579–13584, doi:10.1073/pnas.1517656112.

	Environmental-ecological			
	Air pollution	Toxic waste, ecotoxicity eutrophication	Water quantity and quality	Biodiversity
Wind energy	+	±	N/A	±
Role of context	Minimal effects in manufacturing	Low when recycled properly		Can be minimised by careful site selection of wind power facilities
Line of sight	Sovacool, B.K., M.A. Munoz Perea, A.V. Matamoros, and P. Enevoldsen, 2016: Valuing the manufacturing externalities of wind energy: Assessing the environmental profit and loss of wind turbines in Northern Europe. *Wind Energy*, **19(9)**, 1623–1647, doi:10.1002/we.1941. Wang, S., S. Wang, and P. Smith, 2015: Ecological impacts of wind farms on birds: Questions, hypotheses, and research needs. *Renew. Sustain. Energy Rev.*, **44**, 599–607, doi: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 bodies.	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	Maavara, T. et al., 2020: River dam impacts on biogeochemical cycling. *Nat. Rev. Earth Environ.*, **1**, 103–116, https://doi.org/10.1038/s43017-019-0019-0. Phyoe, W.W. and F. Wang, 2019: A review of carbon sink or source effect on artificial reservoirs. *Int. J. Environ. Sci. Technol.*, **16**, 2161–2174, https://doi.org/10.1007/s13762-019-02237-2. Prairie, Y.T. et al., 2018: Greenhouse Gas Emissions from Freshwater Reservoirs: What Does the Atmosphere See? *Ecosystems*, **21**, 1058–1071, https://doi.org/10.1007/s10021-017- 0198-9. Yan, X., V. Thieu, and J. Garnier, 2021: Long-Term Evolution of Greenhouse Gas Emissions From Global Reservoirs. *Front. Environ. Sci.*, **9**, 289, doi:10.3389/fenvs.2021.705477. Gagnon, L. and J.F. van de Vate, 1997: Greenhouse gas emissions from hydropower: the state of research in 1996. *Energy Policy*, **25(1)**, 7–13, doi:10.1016/S0301-4215(96)00125-5.	Rietzler, A.C., C.R. Botta, M.M. Ribeiro, O. Rocha, and A.L. Fonseca, 2018: Accelerated eutrophication and toxicity in tropical reservoir water and sediments: an ecotoxicological approach. *Environ. Sci. Pollut. Res.*, **25(14)**, 13292–13311, doi:10.1007/s11356-016-7719-5.	Cronin, J., G. Anandarajah, and O. Dessens, 2018: Climate change impacts on the energy system: a review of trends and gaps. *Clim. Change*, **151(2)**, 79–93, doi: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 electricity supply investment needs. *Energy*, **141**, 2081–2090, doi:10.1016/j.energy.2017.11.089. van Vliet, M.T.H. et al., 2016a: Multi-model assessment of global hydropower and cooling water discharge potential under climate change. *Glob. Environ. Change*, **40**, 156–170, doi: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(12)**, 124021, doi:10.1088/1748-9326/11/12/124021. van Vliet, M.T.H.H., D. Wiberg, S. Leduc, and K. Riahi, 2016c: Power-generation system vulnerability and adaptation to changes in climate and water resources. *Nat. Clim. Change*, **6(4)**, 375–380, doi:10.1038/nclimate2903 Yalew, S.G. et al., 2020: Impacts of climate change on energy systems in global and regional scenarios. *Nat. Energy*, **5(10)**, 794–802, doi:10.1038/s41560-020-0664-z. Mukheibir, P., 2013: Potential consequences of projected climate change impacts on hydroelectricity generation. *Clim. Change*, **121(1)**, 67–78, doi:10.1007/s10584-013-0890-5.	Gracey, E.O., and F. Verones, 2016: Impacts from hydropower production on biodiversity in an LCA framework—review and recommendations. *Int. J. Life Cycle Assess.*, **21(3)**, 412–428, doi:10.1007/s11367-016-1039-3. Zarfl, C. et al., 2019: Future large hydropower dams impact global freshwater megafauna. *Sci. Rep.*, **9(1)**, 18531, doi: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(1)**, 638–643, doi:10.1016/j.scitotenv.2013.11.047.

	Environmental-ecological			
	Air pollution	**Toxic waste, ecotoxicity eutrophication**	**Water quantity and quality**	**Biodiversity**
Nuclear	+	±	±	±
Role of context	Has low nitrogen oxides (NO_x), sulphur dioxide (SO_2), particulate matter (PM), and non-methane volatile organic compound (NMVOC) emissions on a life-cycle basis.	Low impacts to ecosystems, acidification, eutrophication, ecotoxicity, ozone depletion, and photochemical ozone creation potential (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., E.G. Hertwich, A. Arvesen, B. Singh, and F. Verones, 2017: Health benefits, ecological threats of low-carbon electricity. *Environ. Res. Lett.*, **12(3)**, 034023, doi:10.1088/1748-9326/aa6047. European Commission Joint Research Centre (EU JRC), 2021: *Technical assessment of nuclear energy with respect to the 'do no significant harm' criteria of Regulation (EU) 2020/852 ('Taxonomy Regulation'). JRC124193*. European Commission, Petten, Netherlands, 387 pp.	Luderer, G. et al., 2019: Environmental co-benefits and adverse side-effects of alternative power sector decarbonization strategies. *Nat. Commun.*, **10(1)**, 1–13, doi:10.1038/s41467-019-13067-8. European Commission Joint Research Centre (EU JRC), 2021: *Technical assessment of nuclear energy with respect to the 'do no significant harm' criteria of Regulation (EU) 2020/852 ('Taxonomy Regulation'). JRC124193*. European Commission, Petten, Netherlands, 387 pp.	Meldrum, J., S. Nettles-Anderson, G. Heath, and J. Macknick, 2013: Life cycle water use for electricity generation: a review and harmonization of literature estimates. *Environ. Res. Lett.*, **8(1)**, 015031, doi:10.1088/1748-9326/8/1/015031. Mouratiadou, I. et al., 2016: The impact of climate change mitigation on water demand for energy and food: An integrated analysis based on the Shared Socioeconomic Pathways. *Environ. Sci. Policy*, **64**, 48–58, doi:10.1016/j.envsci.2016.06.007. European Commission Joint Research Centre (EU JRC), 2021: *Technical assessment of nuclear energy with respect to the 'do no significant harm' criteria of Regulation (EU) 2020/852 ('Taxonomy Regulation'). JRC124193*. European Commission, Petten, Netherlands, 387 pp.	Brook, B.W. and C.J.A. Bradshaw, 2015: Key role for nuclear energy in global biodiversity conservation. *Conserv. Biol.*, **29(3)**, 702–712, doi:10.1111/cobi.12433.
Carbon dioxide (CO_2) capture, utilisation 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., C. Chen, and A.B. Rao, 2007: Cost and performance of fossil fuel power plants with CO_2 capture and storage. *Energy Policy*, **35(9)**, 4444–4454, doi:10.1016/j.enpol.2007.03.009.		Liu, L., M. Hejazi, G. Iyer, and B.A. Forman, 2019: Implications of water constraints on electricity capacity expansion in the United States. *Nat. Sustain.*, **2(3)**, 206–213, doi:10.1038/s41893-019-0235-0.	

	Environmental-ecological			
	Air pollution	**Toxic waste, ecotoxicity eutrophication**	**Water quantity and quality**	**Biodiversity**
Bioenergy	±	NE	±	±
Role of context	Direct use of bioenergy without carbon capture and storage (CCS) leads to air pollutant emissions. For bioenergy, the life cycle assessment of criteria pollutants is considerably different than that for greenhouse gases (GHGs). The impact of bioenergy use on air pollutants needs 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 bioenergy with carbon capture and storage (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 fertilised, bioenergy could have implications for water quality. However, if perennial grasses with low nitrogen 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. et al., 2009: Air quality issues associated with biofuel production and use. In: *Environmental Consequences and Interactions with Changing Land Use. Proceedings of the Scientific Committee on Problems of the Environment (SCOPE) International Biofuels Project Rapid Assessment* [Howarth, R.W. and S. Bringezu, (eds.)], Cornell University, New York, NY, pp. 169–194.	Lee, S.Y. et al., 2019: Waste to bioenergy: a review on the recent conversion technologies. *BMC Energy*, **1(1)**, 4, doi:10.1186/s42500-019-0004-7.	Schyns, J.F., A.Y. Hoekstra, M.J. Booij, R.J. Hogeboom, and M.M. Mekonnen, 2019: Limits to the world's green water resources for food, feed, fiber, timber, and bioenergy. *Proc. Natl. Acad. Sci.*, **116(11)**, 4893–4898, doi:10.1073/pnas.1817380116. Calvin, K. et al., 2021: Bioenergy for climate change mitigation: Scale and sustainability. *GCB Bioenergy*, **13(9)**, 1346–1371, doi:10.1111/gcbb.12863.	Immerzeel, D.J., P.A. Verweij, F. van der Hilst, and A.P.C. Faaij, 2014: Biodiversity impacts of bioenergy crop production: a state-of-the-art review. *GCB Bioenergy*, **6(3)**, 183–209, doi:10.1111/gcbb.12067. Smith, P., J. Price, A. Molotoks, R. Warren, and Y. Malhi, 2018: Impacts on terrestrial biodiversity of moving from a 2°C to a 1.5°C target. *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.*, **376(2119)**, 20160456, doi:10.1098/rsta.2016.0456. Calvin, K. et al., 2021: Bioenergy for climate change mitigation: Scale and sustainability. *GCB Bioenergy*, **13(9)**, 1346–1371, doi:10.1111/gcbb.12863.
Fossil fuel phase-out	+	±	+	+
Role of context	Large air pollution benefits, especially of coal phase-out.	Considerable benefits but replacements 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. et al., 2020: Coal-exit health and environmental damage reductions outweigh economic impacts. *Nat. Clim. Change*, **10(4)**, 308–312, doi:10.1038/s41558-020-0728-x.		Oei, P.-Y. et al., 2020: Coal phase-out in Germany – Implications and policies for affected regions. *Energy*, **196**, 117004, doi:10.1016/j.energy.2020.117004.	Harfoot, M.B.J. et al., 2018: Present and future biodiversity risks from fossil fuel exploitation. *Conserv. Lett.*, **11(4)**, e12448, doi:10.1111/conl.12448.
Geothermal	±	±	–	–
Role of context	Geothermal power plants can meet the most stringent clean air standards, but can also eject more heat than other plants per unit of electricity generated.	–	Impact on ground water depletion and contamination, living organisms, seismicity.	Impact on living organisms.
Line of sight	Dowd, A.M., N. Boughen, P. Ashworth, and S. Carr-Cornish, 2011: Geothermal technology in Australia: Investigating social acceptance. *Energy Policy*, **39**, 6301–6307, https://doi.org/10.1016/j.enpol.2011.07.029. Hunt, T.M., 2001: *Five Lectures on Environmental Effects of Geothermal Utilization*. United Nations University, Geothermal Training Programme, Reykjavík, Iceland, 109 pp. https://orkustofnun.is/gogn/unu-gtp-report/UNU-GTP-2000-01.pdf. Arshad, M., M. Assad, T. Abid, A. Waqar, M. Waqas, and M. Khan. A Techno-Economic Concept of EGS Power Generation in Pakistan. PROCEEDINGS, 44th Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, February 11–13, 2019. https://pangea.stanford.edu/ERE/pdf/IGAstandard/SGW/2019/Arshad.pdf.			

	Environmental-ecological			
	Air pollution	**Toxic waste, ecotoxicity eutrophication**	**Water quantity and quality**	**Biodiversity**
Energy storage for low-carbon grids	+	–	–	±
Role of context	The storage 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 greenhouse gases (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 uses 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 (Energy Storage Association), 2019. Retrieved on December 26 from https://energystorage.org/.	ESA (Energy Storage Association), 2019. Retrieved on December 26 from https://energystorage.org/.	Dehghani-Sanij, A. R., Tharumalingam, E., Dusseault, M. B., & Fraser, R. (2019). Study of energy storage systems and environmental challenges of batteries. Renewable and Sustainable Energy Reviews, 104, 192-208.	Gajardo G, Redón S.Andean hypersaline lakes in the Atacama Desert,northern Chile: Between lithium exploitation and unique biodiversity conservation. Conservation Science and Practice. 2019;1:e94.https://doi.org/10.1111/csp2.94
Demand-side mitigation	+	+	+	+
Role of contexts	Impact varies across behaviours and different pollutants.	Using fewer resources implies producing less toxic waste. Varies across behaviours; circular behaviour reduces toxic waste and carbon dioxide (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	Monforti-Ferrario, F., A. Kona, E. Peduzzi, D. Pernigotti, and E. Pisoni, 2018: The impact on air quality of energy saving measures in the major cities signatories of the Covenant of Mayors initiative. *Environ. Int.*, **118**, 222–234, doi:10.1016/j.envint.2018.06.001. State and Territorial air Pollution Program Administrators (STAPPA), and Association of Local Air Pollution Control Officials (ALAPCO), 1999: *Reducing Greenhouse Gases and Air Pollution: A Menu of Harmonized Options*. 1–14 pp. IPCC, 2018: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 616 pp.	IPCC, 2018: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 616 pp.	IPCC, 2018: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 616 pp.	IPCC, 2018: Global Warming of 1.5°C. *An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 616 pp.

	Environmental-ecological			
	Air pollution	Toxic waste, ecotoxicity eutrophication	Water quantity and quality	Biodiversity
System integration	+	+	+	**NE**
Role of context	By using the synergies within and between sectors, Energy System Integration (ESI) aims to increase flexibility in the energy system, maximise the integration of renewable energy and distributed generation, and reduce environmental impact.	Potential of reducing nitrogen oxides (NO_x) by optimal use of ammonia.	ESI aims to increase flexibility in the energy system such as the link between electricity-water nexus, which can optimise the quantity of water.	
Line of sight	Cambini, C., Congiu, R., Jamasb, T., Llorca, M., & Soroush, G. (2020). Energy Systems Integration: Implications for Public Policy. *Energy Policy*, 143, 111609.	G. Strbac, D. Pudjianto, R. Sansom, P. Djapic, H. Ameli, N. Shah, N. Brandon, A. Hawkes, and M. Qadrdan, "Analysis of Alternative UK Heat Decarbonisation Pathways for the Committee on Climate Change", Imperial College London, Aug. 2018.	NREL (2014) MAKING SUSTAINABLE ENERGY CHOICES: Insights on the Energy/Water/Land Nexus. https://www.nrel.gov/docs/fy15osti/62566.pdf.	

	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, doi:10.1016/j.joule.2020.09.004.	Haegel, N.M. et al., 2019: Terawatt-scale photovoltaics: Transform global energy. *Science*, **364(6443)**, 836–838, doi:10.1126/science.aaw1845.	Green, M.A., 2016: Commercial progress and challenges for photovoltaics. *Nat. Energy*, **1(1)**, 15015, doi: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. et al., 2019: Powering the 21st century by wind energy—Options, facts, figures. *Appl. Phys. Rev.*, **6(3)**, 031303, doi:10.1063/1.5089877.	IRENA, 2019: *Future of wind: Deployment, investment, technology, grid integration and socio-economic aspects (A Global Energy Transformation paper)*. International Renewable Energy Agency (IRENA), Abu Dhabi, United Arab Emirates, 88 pp.	IRENA, 2019: *Future of wind: Deployment, investment, technology, grid integration and socio-economic aspects (A Global Energy Transformation paper)*. International Renewable Energy Agency (IRENA), Abu Dhabi, United Arab Emirates, 88 pp.
Hydroelectric power	+	+	+
Role of context		Globally scalable	Very matured
Line of sight	IRENA (2021) IRENA, 2021: *Renewable Power Generation Costs in 2020*. International Renewable Energy Agency (IRENA), Abu Dhabi, United Arab Emirates, 180 pp. IHA, 2019: *Hydropower Sector Climate Resilience Guide*. International Hydropower Association (IHA), London, UK, 75 pp.	IRENA, 2021: *Renewable Power Generation Costs in 2020*. International Renewable Energy Agency (IRENA), Abu Dhabi, United Arab Emirates, 180 pp.	IRENA, 2021: *Renewable Power Generation Costs in 2020*. International Renewable Energy Agency (IRENA), Abu Dhabi, United Arab Emirates, 180 pp. Killingtveit, Å., 2020: Hydroelectric Power. In: *Future Energy* [Letcher, T.M.B.T.-F.E. (Third E., (ed.)], Elsevier, pp. 315–330.
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	MIT, 2018: *The future of nuclear energy in a carbon-constrained world*. MIT, Cambridge, MA, USA, 272 pp.	MIT, 2018: *The future of nuclear energy in a carbon-constrained world*. MIT, Cambridge, MA, USA, 272 pp.	NEA, 2020: *Unlocking Reductions in the Construction Costs of Nuclear:A Practical Guide*. OECD Publishing, Paris, France, 134 pp.

	Technological		
	Simplicity	**Technological scalability**	**Maturity and technology readiness**
Carbon dioxide (CO_2) capture, utilisation 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. and S. Yaw, 2018: The cost of getting CCS wrong: Uncertainty, infrastructure design, and stranded CO_2. *Int. J. Greenh. Gas Control*, **70**, 1–11, doi:10.1016/j.ijggc.2017.12.011.	Tapia, J.F.D., J.-Y. Lee, R.E.H. Ooi, D.C.Y. Foo, and R.R. Tan, 2018: A review of optimization and decision-making models for the planning of CO_2 capture, utilization and storage (CCUS) systems. *Sustain. Prod. Consum.*, **13**, 1–15, doi:10.1016/j.spc.2017.10.001.	van der Spek, M. et al., 2020: Uncertainty analysis in the techno-economic assessment of CO_2 capture and storage technologies. Critical review and guidelines for use. *Int. J. Greenh. Gas Control*, **100**, 103113, doi:10.1016/j.ijggc.2020.103113.
Bioenergy	–	±	±
Role of context	Logistically challenging requiring widespread infrastructural coordination	While traditional biomass and first-generation biofuels are widely used today, their scalability is limited by resource constraints. Scale-up of bioenergy use for other feedstocks will require advanced technologies such as gasification, Fischer-Tropsch processing, hydrothermal liquefaction (HTL), and pyrolysis. And scaling up these processes will require robust business strategies and optimised use of co-products. Several technological and institutional barriers exist for large-scale bioenergy with carbon capture and storage (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, these are mostly not cost-competitive yet.
Line of sight	Shu, K., U.A. Schneider, and J. Scheffran, 2017: Optimizing the bioenergy industry infrastructure: Transportation networks and bioenergy plant locations. *Appl. Energy*, **192**, 247–261, doi:10.1016/j.apenergy.2017.01.092.	Lee, R.A. and J.-M. Lavoie, 2013: From first- to third-generation biofuels: Challenges of producing a commodity from a biomass of increasing complexity. *Anim. Front.*, **3(2)**, 6–11, doi:10.2527/af.2013-0010.	Baker, S.E. et al., 2020: *Getting to Neutral:Options for Negative Carbon Emissions in California*. Lawrence Livermore National Laboratory, Livermore, California, USA, 178 pp. Daioglou, V. et al., 2020: Bioenergy technologies in long-run climate change mitigation: results from the EMF-33 study. *Clim. Change*, **163(3)**, 1603–1620, doi:10.1007/s10584-020-02799-y.
Fossil fuel phase-out	±	±	+
Role of context	Uncertain. Depends on replacement technologies	Uncertain. Depends on replacement technologies	Several regions have already demonstrated coal phase-out
Line of sight	Jakob, M. et al., 2020: The future of coal in a carbon-constrained climate. *Nat. Clim. Change*, **10(8)**, 704–707, doi:10.1038/s41558-020-0866-1.		Keles, D. and H.Ü. Yilmaz, 2020: Decarbonisation through coal phase-out in Germany and Europe — Impact on Emissions, electricity prices and power production. *Energy Policy*, **141(3)**, 111472, doi:10.1016/j.enpol.2020.111472.
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: *Develop bankable renewable energy projects*. International Renewable Energy Agency (IRENA), Abu Dhabi, United Arab Emirates, 1–8 pp.	Limberger, J. et al., 2018: Geothermal energy in deep aquifers: A global assessment of the resource base for direct heat utilization. *Renew. Sustain. Energy Rev.*, **82, Part 1**, 961–975, doi:10.1016/j.rser.2017.09.084.

	Technological		
	Simplicity	**Technological scalability**	**Maturity and technology readiness**
Energy storage for low-carbon grids	±	+	±
Role of context	Some storage technologies are still in an 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 an early stage of development and need further attention to be widely deployed. Some are very mature.
Line of sight	Belderbos, A., E. Delarue, and W. D'haeseleer, 2016: Calculating the levelized cost of electricity storage. *Energy: Expectations and Uncertainty, 39th IAEE International Conference, IAEE, Norway Jun 19-22, 2016*. Shaqsi, A.Z., K. Sopian, and A. Al-Hinai, 2020: Review of energy storage services, applications, limitations, and benefits. *Energy Reports*, **6**, 288–306, doi:10.1016/j.egyr.2020.07.028.	Shaqsi, A.Z., K. Sopian, and A. Al-Hinai, 2020: Review of energy storage services, applications, limitations, and benefits. *Energy Reports*, **6**, 288–306, doi:10.1016/j.egyr.2020.07.028.	Belderbos, A., E. Delarue, and W. D'haeseleer, 2016: Calculating the levelized cost of electricity storage. *Energy: Expectations and Uncertainty, 39th IAEE International Conference, IAEE, Norway, Jun 19-22, 2016*. Shaqsi, A.Z., K. Sopian, and A. Al-Hinai, 2020: Review of energy storage services, applications, limitations, and benefits. *Energy Reports*, **6**, 288–306, doi:10.1016/j.egyr.2020.07.028.
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 this differs across regions.	Some demand options rely on technological innovations, of which some are at low technology readiness level, 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 level to transmission level is scalable	Currently developments in renewable energy, energy storage, and power electronic technologies have been experienced. However, gaps have also 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; optimisation and control structures to integrate energy systems; improved design, installation and control.
Line of sight	O'Malley, M. et al., 2016: *Energy systems integration. Defining and describing the value proposition*. International Institute of Energy Systems Integration, Golden, CO, USA.	European Commission, 2019. *Orientations towards the first strategic plan for Horizon Europe*, Brussels, Belgium. Available: https://ec.europa.eu/info/sites/info/files/rese arch_and_innovation/strategy_on_research_and_innovation/documents/ec_rtd_orientations-he-strategic-plan_122019.pdf.	ESFRI, 2018: *Developing a Framework for Integrated Energy Network Planning (IEN-P)*. ESFRI roadmap 2018 - strategy report on research infrastructures, Energy System Integration, European Strategy Forum on Research Infrastructures, Milan, Italy pp 50-52. http://roadmap2018.esfri.eu/media/1050/roadmap18-part2.pdf Ruth, M.F. and B. Kroposki, 2014: Energy systems integration: An evolving energy paradigm. *Electr. J.*, **27**, 36–47.

	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. et al., 2019: Terawatt-scale photovoltaics: Transform global energy. *Science.*, **364(6443)**, 836–838, doi:10.1126/science.aaw1845.	Siegmeier, J. et al., 2017: The fiscal benefits of stringent climate change mitigation: an overview. *Clim. Policy*, **18(3)**, 352–367, doi:10.1080/14693062.2017.1400943.
Wind energy	+	+
Role of context	Declining	Globally beneficial
Line of sight	IRENA, 2021: *Renewable Power Generation Costs in 2020*. International Renewable Energy Agency, Abu Dhabi, UAE, 180 pp.	Pai, S., J. Emmerling, L. Drouet, H. Zerriffi, and J. Jewell, 2021: Meeting well-below 2°C target would increase energy sector jobs globally. *One Earth*, **4(7)**, 1026–1036, doi:10.1016/j.oneear.2021.06.005.

	Economic	
	Costs in 2030 and long term	**Employment effects and economic growth**
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: *Renewable Power Generation Costs in 2020*. International Renewable Energy Agency, Abu Dhabi, UAE, 180 pp. 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, doi:10.1073/pnas.1809426115.	Sadoff, C.W. et al., 2015: *Securing Water, Sustaining Growth: Report of the GWP/OECD task force on Water Security and Sustainable Growth*. University of Oxford, Oxford, UK, 180 pp.
Nuclear	±	±
Role of context	Costs for new builds are project/country/region specific. In some countries it is competitive, in others less so. Lifetime extensions are much cheaper than new builds.	Feedback on the economies is positive in some countries. Employment effects are more pronounced during the construction phase.
Line of sight	NEA/IEA/OECD, 2020: *Projected Costs of Generating Electricity 2020*. OECD Publishing, Paris, France, 219 pp. NEA, 2020: *Unlocking Reductions in the Construction Costs of Nuclear:A Practical Guide*. OECD Publishing, Paris, France, 134 pp.	NEA and IAEA, 2018: *Measuring Employment Generated by the Nuclear Power Sector*. NEA, OECD, Boulogne-Billancourt, France, 96 pp. Lee, M.-K., K.-Y. Nam, K.-H. Jeong, B.-J. Min, and Y.-E. Jung, 2009: Contribution of Nuclear Power to the National Economic Development in Korea. *Nucl. Eng. Technol.*, **41(4)**, 549–560, doi:10.5516/NET.2009.41.4.549.
Carbon dioxide (CO_2) capture, utilisation 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., S. Roussanaly, and E.S. Rubin, 2019: Best practices and recent advances in CCS cost engineering and economic analysis. *Int. J. Greenh. Gas Control*, **83**, 91–104, doi:10.1016/j.ijggc.2019.02.006.	Tvinnereim, E. and E. Ivarsflaten, 2016: Fossil fuels, employment, and support for climate policies. *Energy Policy*, **96**, 364–371, doi:10.1016/J.ENPOL.2016.05.052.
Bioenergy	±	+
Role of context	Technology costs of advanced bioenergy pathways are higher compared to alternatives today and, while they are generally anticipated to reduce, high uncertainty exist about future costs.	Potential increase in employment if bioenergy use increases
Line of sight	Daioglou, V. et al., 2020: Bioenergy technologies in long-run climate change mitigation: results from the EMF-33 study. *Clim. Change*, **163(3)**, 1603–1620, doi:10.1007/s10584-020-02799-y.	Ram, M., A. Aghahosseini, and C. Breyer, 2020: Job creation during the global energy transition towards 100% renewable power system by 2050. *Technol. Forecast. Soc. Change*, **151**, 119682, doi:10.1016/j.techfore.2019.06.008.
Fossil fuel phase-out	±	±
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. et al., 2019: Assessing the environmental externalities for biomass- and coal-fired electricity generation in China: A supply chain perspective. *J. Environ. Manage.*, **246**, 758–767, doi:10.1016/j.jenvman.2019.06.047.	He, G. et al., 2020: Enabling a Rapid and Just Transition away from Coal in China. *One Earth*, **3(2)**, 187–194, doi:10.1016/j.oneear.2020.07.012.
Geothermal	+	–
Role of context	Potential for reduction of high depth thanks to technology progress in drilling. Typical costs for geothermal power plants 1870 USD to 5050 USD/ kW depending on size and technology. Potential for LOCE reduction in the long-term. 0.04-0.14 USD to 0.037 to 0.11 USD by 2050	Little impact on employment and economic growth. High capital cost per unit
Line of sight	IRENA, 2017: Renewable Cost Database. International Renewable Energy Agency (IRENA), Abu Dhabi, United Arab Emirates IRENA, 2017: *Geothermal Power: Technology Brief*. IRENA, Abu Dhabi, United Arab Emirates, 28 pp. US Department of Energy, Geothermal FAQs. https://www.energy.gov/eere/geothermal/geothermal-faqs. a-IRENA, 2017. Renewable Cost Database, International Renewable Energy Agency (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	

	Economic	
	Costs in 2030 and long term	Employment effects and economic growth
Energy storage for low-carbon grids	+	+
Role of context	Various energy storage technologies also differ in their cost (capital, running and maintenance, labour, and replacement after some intervals). Although there is some prediction in the literature, there is uncertainty, and perfect insight is not possible.	Skilled employment in manufacturing, maintenance and installation companies
Line of sight	Shaqsi et al., (2020) Shaqsi, A.Z., K. Sopian, and A. Al-Hinai, 2020: Review of energy storage services, applications, limitations, and benefits. *Energy Reports*, **6**, 288–306, doi:10.1016/j.egyr.2020.07.028.	Ram, M., Aghahosseini, A., & Breyer, C. (2020). Job creation during the global energy transition towards 100% renewable power system by 2050. Technological Forecasting and Social Change, 151, 119682.
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	Linares, P., P. Pintos, and K. Würzburg, 2017: Assessing the potential and costs of reducing energy demand. *Energy Transitions*, **1(1)**, 4, doi:10.1007/s41825-017-0004-5. IPCC, 2018: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 616 pp. Füllemann, Y., V. Moreau, M. Vielle, and F. Vuille, 2020: Hire fast, fire slow: the employment benefits of energy transitions. *Econ. Syst. Res.*, **32(2)**, 202–220, doi:10.1080/09535314.2019.1695584. Cambridge Econometrics, 2015: *Assessing the Employment and Social Impact of Energy Efficiency*. Cambridge Econometrics, Cambridge, UK, 139 pp. ILO, 2018: *World Employment and Social Outlook 2018 – Greening with jobs*. International Labour Organization (ILO), Geneva, Switzerland, 32 pp.	
System integration	+	+
Role of context	The amount of cost reduction has been reported in in Cambini et al. (2020).	The cost reduction leads to economic growth through providing opportunity to invest in other fields. Furthermore, developing renewable energies can increase employment rate.
Line of sight	Cambini, C., Congiu, R., Jamasb, T., Llorca, M., & Soroush, G. (2020). Energy Systems Integration: Implications for Public Policy. Energy Policy, 143, 111609.	= Cambini, C., Congiu, R., Jamasb, T., Llorca, M., & Soroush, G. (2020). Energy Systems Integration: Implications for Public Policy. Energy Policy, 143, 111609. Montt, G., Capaldo, J., Esposito, M., Harsdorff, M., Maitre, N., & Samaan, D. (2018). Employment and the role of workers and employers in a green economy. *World Employment and Social Outlook*, *2018*(2), 37–68.

	Socio-cultural		
	Public acceptance	**Effects on health and well-being**	**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, D.L. and J.L. Arvai, 2018: Engaging attribute tradeoffs in clean energy portfolio development. *Energy Policy*, **115(October 2017)**, 221–229, doi:10.1016/j.enpol.2018.01.021. Boudet, H.S., 2019: Public perceptions of and responses to new energy technologies. *Nat. Energy*, **4(6)**, 446–455, doi:10.1038/s41560-019-0399-x. Faiers, A. and C. Neame, 2006: Consumer attitudes towards domestic solar power systems. *Energy Policy*, **34(14)**, 1797–1806, doi:10.1016/j.enpol.2005.01.001. Hanger, S. et al., 2016: Community acceptance of large-scale solar energy installations in developing countries: Evidence from Morocco. *Energy Res. Soc. Sci.*, **14**, 80–89, doi:10.1016/j.erss.2016.01.010. Hazboun, S.O. and H.S. Boudet, 2020: Public preferences in a shifting energy future: Comparing public views of eight energy sources in North America's Pacific Northwest. *Energies*, **13(8)**, 1–21, doi:10.3390/en13081940. Jobin, M. and M. Siegrist, 2018: We choose what we like – Affect as a driver of electricity portfolio choice. *Energy Policy*, **122(August)**, 736–747. Korcaj, L., U.J.J. Hahnel, and H. Spada, 2015: Intentions to adopt photovoltaic systems depend on homeowners' expected personal gains and behavior of peers. *Renew. Energy*, **75**, 407–415, doi:10.1016/j.renene.2014.10.007. Ma, C. et al., 2015: Consumers' willingness to pay for renewable energy: A meta-regression analysis. *Resour. Energy Econ.*, **42**, 93–109, doi:10.1016/j.reseneeco.2015.07.003. Mcgowan, F. and R. Sauter, 2005: *Public Opinion on Energy Research: A Desk Study for the Research Councils*. University of Sussex, Brighton, UK, 35 pp. Palm, A., 2017: Peer effects in residential solar photovoltaics adoption—A mixed methods study of Swedish users. *Energy Res. Soc. Sci.*, **26**, 1–10, doi:10.1016/J.ERSS.2017.01.008. Steg, L., 2018: Limiting climate change requires research on climate action. *Nat. Clim. Change*, **8(9)**, 759–761, doi:10.1038/s41558-018-0269-8. Vasseur, V. and R. Kemp, 2015: The adoption of PV in the Netherlands: A statistical analysis of adoption factors. *Renew. Sustain. Energy Rev.*, **41**, 483–494, doi:10.1016/j.rser.2014.08.02. Whitmarsh, L. et al., 2011b: *Public Attitudes, Understanding, and Engagement in relation to Low-Carbon Energy: A selective review of academic and non-academic literatures*. 180 pp.	Shindell, D., G. Faluvegi, K. Seltzer, and C. Shindell, 2018: Quantified, localized health benefits of accelerated carbon dioxide emissions reductions. *Nat. Clim. Change*, **8(4)**, 291–295, doi:10.1038/s41558-018-0108-y.	McCauley, D. et al., 2019: Energy justice in the transition to low carbon energy systems: Exploring key themes in interdisciplinary research. *Appl. Energy*, **233–234(November 2018)**, 916–921, doi:10.1016/j.apenergy.2018.10.005.

	Socio-cultural		
	Public acceptance	**Effects on health and well-being**	**Distributional effects**
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 issues at some places	There is 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: *The Reputation of Energy Sources: American Public Opinion in a Global Context*. https://www.ipsos.com/sites/default/files/publication/2004-12/IpsosPA_POV_ReputationofEnergySources.pdf, Last Accessed 28 October 2022. Rand, J. and B. Hoen, 2017: Thirty years of North American wind energy acceptance research: What have we learned? *Energy Res. Soc. Sci.*, **29(February)**, 135–148, doi:10.1016/j.erss.2017.05.019. Devine-Wright, P. 2005: Beyond NIMBYism: Towards an integrated framework for understanding public perceptions of wind energy. *Wind Energy*, **8(2)**, 125–139, doi:10.1002/we.124. Bates, A. and J. Firestone, 2015: A comparative assessment of proposed offshore wind power demonstration projects in the United States. *Energy Res. Soc. Sci.*, **10**, 192–205, doi:10.1016/j.erss.2015.07.007. Hoen, B. et al., 2019: Attitudes of U.S. Wind Turbine Neighbors: Analysis of a Nationwide Survey. *Energy Policy*, **134(October 2018)**, 110981, doi:10.1016/j.enpol.2019.110981. Steg, L. 2018: Limiting climate change requires research on climate action. *Nat. Clim. Change*, **8(9)**, 759–761, doi:10.1038/s41558-018-0269-8.	Delicado, A., Figueiredo, E., and Silva, L. (2016). Community perceptions of renewable energies in Portugal: impacts on environment, landscape and local development. Energy Research and Social Science, **13**. 84–93. https://doi.org/10.1016/j.erss.2015.12.007.	Avila, S. (2018). Environmental justice and the expanding geography of wind power conflicts. *Sustainability Science*, **13(3),** 599-616. https://doi.org/10.1007/s11625-018-0547-4. Liljenfeldt, J. and Pettersson, Ö. (2017). Distributional justice in Swedish wind power development–An odds ratio analysis of windmill localization and local residents' socio-economic characteristics. *Energy Policy*, **105**, 648-657. https://doi.org/10.1016/j.enpol.2017.03.007. Liebe, U., Bartczak, A., and Meyerhoff, J. (2017). A turbine is not only a turbine: The role of social context and fairness characteristics for the local acceptance of wind power. *Energy Policy*, **107**, 300-308. https://doi.org/10.1016/j.enpol.2017.04.043

	Socio-cultural		
	Public acceptance	**Effects on health and well-being**	**Distributional effects**
Hydroelectric power	±	±	–
Role of context	New large hydropower is controversial in some areas if local residents and ecosystems are 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, and so affecting distributional and equity aspects.
Line of sight	Boyd, A.D., J. Liu, and J.D. Hmielowski, 2019: Public support for energy portfolios in Canada: How information about cost and national energy portfolios affect perceptions of energy systems. *Energy Environ.*, **30**, 322–340, https://doi.org/10.1177/0958305X18790958. Bronfman, N.C., R.B. Jiménez, P.C. Arévalo, and L.A. Cifuentes, 2012: Understanding social acceptance of electricity generation sources. *Energy Policy*, **46**, 246–252, https://doi.org/10.1016/j.enpol.2012.03.057. Bronfman, N.C., R.B. Jiménez, P.C. Arevalo, and L.A. Cifuentes, 2015: Public Acceptance of Electricity Generation Sources: The Role of Trust in Regulatory Institutions. *Energy Environ.*, **26**, 349–368, https://doi.org/10.1260/0958-305x.26.3.349. Gormally, A.M., C.G. Pooley, J.D. Whyatt, and R.J. Timmis, 2014: "They made gunpowder… yes down by the river there, that's your energy source": attitudes towards community renewable energy in Cumbria. *Local Environ.*, **19**, 915–932, https://doi.org/10.1080/13549839.2013.810206. Hazboun, S.O. and H.S. Boudet, 2020: Public preferences in a shifting energy future: Comparing public views of eight energy sources in North America's Pacific Northwest. *Energies*, **13**, 1–21, https://doi.org/10.3390/en13081940. Kaldellis, J.K., 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(2013)**, 197–208, doi:10.1016/j.renene.2012.10.045. Karlstrøm, H. and M. Ryghaug, 2014: Public attitudes towards renewable energy technologies in Norway. The role of party preferences. *Energy Policy*, **67**, 656–663, https://doi.org/10.1016/j.enpol.2013.11.049. McCartney, M., 2009: Living with dams: managing the environmental impacts. *Water Policy*, **11**, 121–139, https://doi.org/10.2166/wp.2009.108. Plum, C., R. Olschewski, M. Jobin, and O. van Vliet, 2019: Public preferences for the Swiss electricity system after the nuclear phase-out: A choice experiment. *Energy Policy*, **130**, 181–196, https://doi.org/10.1016/j.enpol.2019.03.054. Rudolf, M., R. Seidl, C. Moser, P. Krütli, and M. Stauffacher, 2014: Public preference of electricity options before and after Fukushima. *J. Integr. Environ. Sci.*, **11**, 1–15, https://doi.org/10.1080/1943815X.2014.881887. Steg, L., 2018: Limiting climate change requires research on climate action. *Nat. Clim. Change*, **8(9)**, 759–761, doi:10.1038/s41558-018-0269-8.	Lerer, L.B. and T. Scudder, 1999: Health impacts of large dams. *Environ. Impact Assess. Rev.*, **19(2)**, 113–123, doi:10.1016/S0195-9255(98)00041-9. Calder, R.S.D. et al., 2016: Future Impacts of Hydroelectric Power Development on Methylmercury Exposures of Canadian Indigenous Communities. *Environ. Sci. Technol.*, **50(23)**, 13115–13122, doi:10.1021/acs.est.6b04447. Phung, D. et al., 2021: Hydropower dams, river drought and health effects: A detection and attribution study in the lower Mekong Delta Region. *Clim. Risk Manag.*, **32**, 100280, doi:10.1016/j.crm.2021.100280.	Nguyen, K.C., J.J. Katzfey, J. Riedl, and A. Troccoli, 2017: Potential impacts of solar arrays on regional climate and on array efficiency. *Int. J. Climatol.*, **37**, 4053–4064, https://doi.org/10.1002/joc.4995. Obour, P.B., K. Owusu, E.A. Agyeman, A. Ahenkan, and À.N. Madrid, 2016: The impacts of dams on local livelihoods: a study of the Bui Hydroelectric Project in Ghana. *Int. J. Water Resour. Dev.*, **32(2)**, 286–300, doi:10.1080/07900627.2015.1022892. Owusu, K., A.B. Asiedu, P.W.K. Yankson, and Y.A. Boafo, 2019: Impacts of Ghana's Bui dam hydroelectricity project on the livelihood of downstream non-resettled communities. *Sustain. Sci.*, **14**, 487–499. Siciliano, G. and Urban, F., 2017: Equity-based natural resource allocation for infrastructure development: evidence from large hydropower dams in Africa and Asia. *Ecological Economics*, **134**, 130-139. https://doi.org/10.1016/j.ecolecon.2016.12.034. Gunawardena, U.P., 2010: Inequalities and externalities of power sector: A case of Broadlands hydropower project in Sri Lanka. *Energy Policy*, **38(2)**, 726-734. https://doi.org/10.1016/j.enpol.2009.10.017. Lebel, L., Lebel, P., Manorom, K., and Yishu, Z., 2019: Gender in Development Discourses of Civil Society Organisations and Mekong Hydropower Dams. *Water Alternatives*, **12(1)**, 192–220.

	Socio-cultural		
	Public acceptance	**Effects on health and well-being**	**Distributional effects**
Nuclear	±	±	±
Role of context	In some countries public acceptance is low, in others it is higher, depending 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, there are 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, D.K., K. Haynes, R. van den Honert, J. McAneney, and W. Poortinga, 2014: Nuclear power in Australia: A comparative analysis of public opinion regarding climate change and the fukushima disaster. *Energy Policy*, **65**, 644–653, doi:10.1016/j.enpol.2013.09.047. Bolsen, T. and F.L. Cook, 2008: The polls – Trends: Public opinion on energy policy: 1974-2006. *Public Opin. Q.*, **72**, 364–388, doi:10.1093/poq/nfn019. Corner, A. et al., 2011: Nuclear power, climate change and energy security: Exploring British public attitudes. *Energy Policy*, **39(9)**, 4823–4833, doi:10.1016/j.enpol.2011.06.037. Gupta, K., M.C. Nowlin, J.T. Ripberger, H.C. Jenkins-Smith, and C.L. Silva, 2019: Tracking the nuclear 'mood' in the United States: Introducing a long term measure of public opinion about nuclear energy using aggregate survey data. *Energy Policy*, **133**, 110888, https://doi.org/10.1016/j.enpol.2019.110888. Hobman, E.V. and P. Ashworth, 2013: Public support for energy sources and related technologies: The impact of simple information provision. *Energy Policy*, **63**, 862–869, doi:10.1016/j.enpol.2013.09.011. Jobin, M., V.H.M. Visschers, O.P.R. van Vliet, J. Árvai, and M. Siegrist, 2019: Affect or information? Examining drivers of public preferences of future energy portfolios in Switzerland. *Energy Res. Soc. Sci.*, **52(December 2018)**, 20–29, doi:10.1016/j.erss.2019.01.016. Pampel, F.C., 2011: Support for nuclear energy in the context of climate change: Evidence from the European Union. *Organ. Environ.*, **24(3)**, 249–268, doi:10.1177/1086026611422261. Poortinga, W., M. Aoyagi, and N.F. Pidgeon, 2013: Public perceptions of climate change and energy futures before and after the Fukushima accident: A comparison between Britain and Japan. *Energy Policy*, **62**, 1204–1211, doi:10.1016/j.enpol.2013.08.015. Siegrist, M. and V.H.M. Visschers, 2013: Acceptance of nuclear power: The Fukushima effect. *Energy Policy*, **59**, 112–119, doi:10.1016/j.enpol.2012.07.051. Soni, A., 2018: Out of sight, out of mind? Investigating the longitudinal impact of the Fukushima nuclear accident on public opinion in the United States. *Energy Policy*, **122**, 169–175, doi:10.1016/j.enpol.2018.07.024. Tsujikawa, N., S. Tsuchida, and T. Shiotani, 2016: Changes in the Factors Influencing Public Acceptance of Nuclear Power Generation in Japan Since the 2011 Fukushima Daiichi Nuclear Disaster. *Risk Analysis*, **36(1)**, 98–113, doi:10.1111/risa.12447. Steg, L., 2018: Limiting climate change requires research on climate action. *Nat. Clim. Change*, **8(9)**, 759–761, doi:10.1038/s41558-018-0269-8.	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., C. Bauer, and A. Simons, 2014: Human health impacts in the life cycle of future European electricity generation. *Energy Policy*, **74**, S31–S44, doi:10.1016/j.enpol.2014.03.034. Longmuir, C. and V.I.O. Agyapong, 2021: Social and Mental Health Impact of Nuclear Disaster in Survivors: A Narrative Review. *Behav. Sci. (Basel).*, **11(8)**, 113, doi:10.3390/bs11080113. US EPA, 2022: *Radiation Health Effects*. https://www.epa.gov/radiation/radiation-health-effects. (Accessed on June 3, 2022.) Hasegawa, A. et al., 2015: Health effects of radiation and other health problems in the aftermath of nuclear accidents, with an emphasis on Fukushima. *Lancet*, **386(9992)**, 479–488, doi:10.1016/S0140-6736(15)61106-0.	Brown, D.A., 2011: Comparative ethical issues entailed in the geological disposal of radioactive waste and carbon dioxide in the light of climate change, In *Geological Disposal of Carbon Dioxide and Radioactive Waste: A Comparative Assessment* [Toth, F.L., (ed.)], Springer, Dordrecht, Netherlands, pp. 317–337. IAEA and Nuclear Technology, 2009: *Nuclear Technology and Economic Development in the Republic of Korea*, International Atomic Energy Agency (IAEA), Vienna, Austria, 148 pp. IAEA, 2016: *Nuclear power and sustainable development*, International Atomic Energy Agency (IAEA),Vienna, Austria, 130 pp.

	Socio-cultural		
	Public acceptance	**Effects on health and well-being**	**Distributional effects**
Carbon dioxide (CO_2) capture, utilisation and storage	–	±	±
Role of context	Many people are unfamiliar with carbon capture and storage (CCS), so have not formed firm opinions. Some firmly reject CCS; some are concerned that CCS may avoid making greenhouse gas (GHG) emission reductions.	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.	Protects future generation against negative impacts of climate change, but a lot of uncertainty about the technology for future generations.
Line of sight	Brown, D.A., 2011: Comparative ethical issues entailed in the geological disposal of radioactive waste and carbon dioxide in the light of climate change. In: *Geological disposal of carbon dioxide and radioactive waste: A comparative assessment* [Toth, F.L., (ed.)], Springer, Dordrecht, Netherlands, pp. 317–337. Science for Environment Policy: European Commission DG Environment News Alert Service, edited by SCU, The University of the West of England, Bristol, UK. Jacobson, M.Z., 2019: The health and climate impacts of carbon capture and direct air capture. *Energy Environ. Sci.*, **12(12)**, 3567–3574, 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 favourably 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 on global trade. Costs and benefits of bioenergy could be unevenly distributed.
Line of sight	Poortinga, W., M. Aoyagi, and N.F. Pidgeon, 2013: Public perceptions of climate change and energy futures before and after the Fukushima accident: A comparison between Britain and Japan. *Energy Policy*, **62**, 1204–1211, doi:10.1016/j.enpol.2013.08.015. Demski, C., C. Butler, K.A. Parkhill, A. Spence, and N.F. Pidgeon, 2015: Public values for energy system change. *Glob. Environ. Change*, **34**, 59–69, doi:10.1016/j.gloenvcha.2015.06.014. Haikola, S., A. Hansson, and J. Anshelm, 2019: From polarization to reluctant acceptance–bioenergy with carbon capture and storage (BECCS) and the post-normalization of the climate debate. *J. Integr. Environ. Sci.*, **16(1)**, 45–69, doi:10.1080/1943815X.2019.1579740.	Hess, P. et al., 2009: Air quality issues associated with biofuel production and use. In: *Environmental Consequences and Interactions with Changing Land Use. Proceedings of the Scientific Committee on Problems of the Environment (SCOPE) International Biofuels Project Rapid Assessment* [Howarth, R.W. and S. Bringezu, (eds.)], Cornell University, New York, NY, USA, pp. 169–194. Scovronick, N. and P. Wilkinson, 2014: Health impacts of liquid biofuel production and use: A review. *Glob. Environ. Change*, **24**, 155–164, doi:10.1016/j.gloenvcha.2013.09.011.	Ram, M., A. Aghahosseini, and C. Breyer, 2020: Job creation during the global energy transition towards 100% renewable power system by 2050. *Technol. Forecast. Soc. Change*, **151**, 119682, doi:10.1016/j.techfore.2019.06.008. Muratori, M., K. Calvin, M. Wise, P. Kyle, and J. Edmonds, 2016: Global economic consequences of deploying bioenergy with carbon capture and storage (BECCS). *Environ. Res. Lett.*, **11(9)**, 095004, doi:10.1088/1748-9326/11/9/095004. Daioglou, V. et al., 2020: Implications of climate change mitigation strategies on international bioenergy trade. *Clim. Change*, **163(3)**, 1639–1658, doi:10.1007/s10584-020-02877-1.
Fossil fuel phase-out	+	+	+
Role of context	Natural gas is evaluated somewhat more favourably than coal and oil; acceptability of fossil energy higher in countries that strongly rely on them		
Line of sight	Cutler, D. and 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, doi:10.1001/jama.2018.7351. Lelieveld, J. et al., 2019: Effects of fossil fuel and total anthropogenic emission removal on public health and climate. *Proc. Natl. Acad. Sci.*, **116(15)**, 7192–7197, doi:10.1073/pnas.1819989116. Nansai, K. et al., 2021: Consumption in the G20 nations causes particulate air pollution resulting in two million premature deaths annually. *Nat. Commun.*, **12(1)**, 6286, doi:10.1038/s41467-021-26348-y. Mikati, I., A.F. Benson, T.J. Luben, J.D. Sacks, and J. Richmond-Bryant, 2018: Disparities in Distribution of Particulate Matter Emission Sources by Race and Poverty Status. *Am. J. Public Health*, **108(4)**, 480–485, doi:10.2105/AJPH.2017.304297. Zhang, Y. et al., 2018: Long-term trends in the ambient $PM_{2.5}$ and O_3 related mortality burdens in the United States under emission reductions from 1990 to 2010. *Atmos. Chem. Phys.*, **18(20)**, 15003–15016, doi:10.5194/acp-18-15003-2018.		

	Socio-cultural		
	Public acceptance	**Effects on health and well-being**	**Distributional effects**
Geothermal	±	–	±
Role of context	Perceived as relatively environmentally-friendly, but with 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	Dowd, A.M., N. Boughen, P. Ashworth, and S. Carr-Cornish, 2011: Geothermal technology in Australia: Investigating social acceptance. *Energy Policy*, **39(10)**, 6301–6307, doi:10.1016/j.enpol.2011.07.029. Hazboun, S.O. and H.S. Boudet, 2020: Public preferences in a shifting energy future: Comparing public views of eight energy sources in North America's Pacific Northwest. *Energies*, **13(8)**, 1–21, doi:10.3390/en13081940. Karytsas, S., O. Polyzou, and C. Karytsas, 2019: Social Aspects of Geothermal Energy in Greece. In: *Lecture Notes in Energy* [Manzella, A., A. Allansdottir, and A. Pellizzone, (eds.)], Springer, Cham, Switzerland, pp. 123–144. Pellizzone, A., A. Allansdottir, R. De Franco, G. Muttoni, and A. Manzella, 2015: Exploring public engagement with geothermal energy in southern Italy: A case study. *Energy Policy*, **85(2015)**, 1–11, doi:10.1016/j.enpol.2015.05.002. Steel, B.S., J.C. Pierce, R.L. Warner, and N.P. Lovrich, 2015: Environmental Value Considerations in Public Attitudes About Alternative Energy Development in Oregon and Washington. *Environ. Manage.*, **55(3)**, 634–645, doi:10.1007/s00267-014-0419-3. Tampakis, S., G. Tsantopoulos, G. Arabatzis, and I. Rerras, 2013: Citizens' views on various forms of energy and their contribution to the environment. *Renew. Sustain. Energy Rev.*, **20**, 473–482, doi:10.1016/j.rser.2012.12.027. Walker, G., 1995: Renewable energy and the public. *Land use policy*, **12(1)**, 49–59, doi:10.1016/0264-8377(95)90074-C.	Shortall, R., Davidsdottir, B., and Axelsson, G., 2015: Geothermal energy for sustainable development: A review of sustainability impacts and assessment frameworks. *Renewable and Sustainable Energy Reviews*, **44**, 391-406. https://doi.org/10.1016/j.rser.2014.12.020.	Shortall, R., Davidsdottir, B., and Axelsson, G., 2015: Geothermal energy for sustainable development: A review of sustainability impacts and assessment frameworks. *Renewable and Sustainable Energy Reviews*, **44**, 391-406. https://doi.org/10.1016/j.rser.2014.12.020.
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 electric vehicle (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 such as the healthcare sector which rely mainly on 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. There are global supply chain issues with some materials, which could be solved through local recycling.
Line of sight	Godfrey, Bruce. The Role of Energy Storage: In Australia's Future Energy Supply Mix. Australian Council of Learned Academies, 2017. Agnew, S. and P. Dargusch, 2017: Consumer preferences for household-level battery energy storage. *Renew. Sustain. Energy Rev.*, **75**, 609–617, doi:10.1016/j.rser.2016.11.030. Emmerich, P. et al., 2020: Public acceptance of emerging energy technologies in context of the German energy transition. *Energy Policy*, **142**, 111516, doi:10.1016/j.enpol.2020.111516. Michaels, L. and Y. Parag, 2016: Motivations and barriers to integrating 'prosuming' services into the future decentralized electricity grid: Findings from Israel. *Energy Res. Soc. Sci.*, **21**, 70–83, doi:10.1016/j.erss.2016.06.023. Thomas, G., C. Demski, and N. Pidgeon, 2019: Deliberating the social acceptability of energy storage in the UK. *Energy Policy*, **133**, doi:10.1016/j.enpol.2019.110908. Zaunbrecher, B.S., T. Bexten, M. Wirsum, and M. Ziefle, 2016: What is Stored, Why, and How? Mental Models, Knowledge, and Public Acceptance of Hydrogen Storage. *Energy Procedia*, **99**, 108–119, doi:10.1016/j.egypro.2016.10.102.		

	Socio-cultural		
	Public acceptance	Effects on health and well-being	Distributional effects
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, improve 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	IEA, 2019: *Multiple Benefits of Energy Efficiency*. International Energy Agency (IEA), Paris, France. https://www.iea.org/reports/multiple-benefits-of-energy-efficiency. US EPA, 2018: *Quantifying the Emissions and Health Benefits of Energy Efficiency and Renewable Energy*. US Environmental Protection Agency (US EPA), Washington DC, USA, 68 pp. Kniesner, T.J. and G. Rustamov, 2018: Differential and Distributional Effects of Energy Efficiency Surveys: Evidence from Electricity Consumption. *J. Benefit-Cost Anal.*, **9(3)**, 375–406, doi:10.1017/bca.2018.17. Sorrell, S., 2015: Reducing energy demand: A review of issues, challenges and approaches. *Renew. Sustain. Energy Rev.*, **47**, 74–82, doi:10.1016/J.RSER.2015.03.002. Ogbeide-Osaretin, E.N., 2021: Analysing energy consumption and poverty reduction nexus in Nigeria. *Int. J. Sustain. Energy*, **40(5)**, 477–493, doi:10.1080/14786451.2020.1815744.		
System integration	±	+	LE
Role of context	Most evidence is on the different aspects of system integration, not the system as a whole. Public acceptance will be higher when investment costs are removed and privacy issues are addressed. Extending transmission lines is generally evaluated negatively. Energy independence and being self-sufficient are positively evaluated.	Reducing air pollution prevents some diseases.	
Line of sight	Leijten, F.R.M. et al., 2014: Factors that influence consumers' acceptance of future energy systems: the effects of adjustment type, production level, and price. *Energy Effic.*, **7(6)**, 973–985, doi:10.1007/s12053-014-9271-9. Lienert, P., B. Suetterlin, and M. Siegrist, 2015: Public acceptance of the expansion and modification of high-voltage power lines in the context of the energy transition. *Energy Policy*, **87(November 2017)**, 573–583, doi:10.1016/j.enpol.2015.09.023. Michaels, L. and Y. Parag, 2016: Motivations and barriers to integrating 'prosuming' services into the future decentralized electricity grid: Findings from Israel. *Energy Res. Soc. Sci.*, **21**, 70–83, doi:10.1016/j.erss.2016.06.023. Spence, A. et al., 2015: Public perceptions of demand-side management and a smarter energy future. *Nature Climate Change*, **5**, 550–554.		

	Institutional		
	Political acceptance	Institutional capacity, governance, cross-sectoral coordination	Legal and administrative capacity
Solar energy	±	+	+
Role of context	Opposed by fossil fuel 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 US energy transition: Case studies of solar, wind, biofuels and electric vehicles policy. *Energy Policy*, **113**, 76–86, doi:10.1016/j.enpol.2017.10.0 57.	Creutzig, F. et al., 2017: The underestimated potential of solar energy to mitigate climate change. *Nat. Energy*, **2(9)**, doi:10.1038/nenergy.2017.140.	Das, S., E. Hittinger, and E. Williams, 2020: Learning is not enough: Diminishing marginal revenues and increasing abatement costs of wind and solar. *Renew. Energy*, **156**, 634-644, doi:10.1016/j.renene.2020.03.082.
Wind energy	±	±	–
Role of context	Opposed by fossil fuel 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 US energy transition: Case studies of solar, wind, biofuels and electric vehicles policy. *Energy Policy*, **113**, 76–86, doi:10.1016/j.enpol.2017.10.057.	IRENA, 2019: *Future of wind: Deployment, investment, technology, grid integration and socio-economic aspects (A Global Energy Transformation paper)*. International Renewable Energy Agency (IRENA), Abu Dhabi, United Arab Emirates, 88 pp.	Das, S., E. Hittinger, and E. Williams, 2020: Learning is not enough: Diminishing marginal revenues and increasing abatement costs of wind and solar. *Renew. Energy*, **156**, 634-644, doi:10.1016/j.renene.2020.03.082.

	Institutional		
	Political acceptance	Institutional capacity, governance, cross-sectoral coordination	Legal and administrative capacity
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, Å., 2020: Hydroelectric Power. In: Future Energy [Letcher, T.M.B.T.-F.E. (Third E., (ed.)], Elsevier, Boca Raton, pp. 315–330.	OECD, 2015: OECD Principles on Water Governance, www.oecd.org/governance/oecd-principles-onwater-governance.htm OECD, 2011: *Water Governance in OECD Countries: A multi-level approach*. OECD, Paris, France. 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(47)**, 11891 LP – 11898, doi:10.1073/pnas.1809426115.	Ito, S., S. El Khatib, and M. Nakayama, 2016: Conflict over a hydropower plant project between Tajikistan and Uzbekistan. *Int. J. Water Resour. Dev.*, **32(5)**, 692–707, doi:10.1080/07900627.2015.1076381.
Nuclear	±	–	±
Role of context	Similar to public acceptance, political support in some countries is low, while in others is high.	Lengthy licensing process, varying political conditions and support, regulatory regimes, complex financial framework	It differs across countries, depending on 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 need to be addressed, including facilities and equipment, as well as human and financial resources, and the legal and regulatory framework.
Line of sight	NEA, 2020: *Unlocking Reductions in the Construction Costs of Nuclear:A Practical Guide*. OECD Publishing, Paris, France, 134 pp.	MIT, 2018: *The future of nuclear energy in a carbon-constrained world*. MIT, Cambridge, MA, USA, 272 pp.	MIT, 2018: *The future of nuclear energy in a carbon-constrained world*. MIT, Cambridge, MA, USA, 272 pp.
Carbon dioxide (CO_2) capture, utilisation and storage	±	+	±
Role of context	Varies across countries	Several new schemes globally incentivise CCUS sufficiently	Need for robust monitoring and verification
Line of sight	Xenias, D. and L. Whitmarsh, 2018: Carbon capture and storage (CCS) experts' attitudes to and experience with public engagement. *Int. J. Greenh. Gas Control*, **78**, 103–116, doi:10.1016/j.ijggc.2018.07.030.	Esposito, R.A., V.A. Kuuskraa, C.G. Rossman, and M.M. Corser, 2019: Reconsidering CCS in the US fossil-fuel fired electricity industry under section 45Q tax credits. *Greenh. Gases Sci. Technol.*, **9(6)**, 1288–1301, doi:10.1002/ghg.1925.	
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., R.L. Graham, B. Hektor, and C. Rakos, 1999: Critical factors to bioenergy implementation. *Biomass and Bioenergy*, **17(2)**, 113–126, doi:10.1016/S0961-9534(99)00028-8.	Alsaleh, M., A.S. Abdul-Rahim, and M.M. Abdulwakil, 2021: The importance of worldwide governance indicators for transitions toward sustainable bioenergy industry. *J. Environ. Manage.*, **294**, 112960, doi:10.1016/j.jenvman.2021.112960. Fridahl, M. and M. Lehtveer, 2018: Bioenergy with carbon capture and storage (BECCS): Global potential, investment preferences, and deployment barriers. *Energy Res. Soc. Sci.*, **42**, 155–165, doi:10.1016/j.erss.2018.03.019.	Torvanger, A., 2019: Governance of bioenergy with carbon capture and storage (BECCS): accounting, rewarding, and the Paris agreement. *Clim. Policy*, **19(3)**, 329–341, doi:10.1080/14693062.2018.1509044.
Fossil fuel phase-out	+	±	–
Role of context	Several governments are indicating support for coal phase-out such as PPCA.	It would require change in fossil fuel subsidy mechanisms	Susceptible to leakage and other effects
Line of sight	Jewell, J., V. Vinichenko, L. Nacke, and A. Cherp, 2019: Prospects for powering past coal. *Nat. Clim. Change*, **9(8)**, 592–597, doi:10.1038/s41558-019-0509-6.	Kalkuhl, M. et al., 2019: Successful coal phase-out requires new models of development. *Nat. Energy*, **4(11)**, 897–900, doi:10.1038/s41560-019-0500-5.	Nielsen, T., N. Baumert, A. Kander, M. Jiborn, and V. Kulionis, 2020: The risk of carbon leakage in global climate agreements. *Int. Environ. Agreements Polit. Law Econ.*, **21(2)**, 147–163, doi:10.1007/s10784-020-09507-2.

	Institutional		
	Political acceptance	**Institutional capacity, governance, cross-sectoral coordination**	**Legal and administrative capacity**
Geothermal	+	+	NE
Role of context	Mostly positive	Some countries are providing policy support in the form of risk guarantees, investment grants to mitigate uncertain drilling operation outcomes and high upfront costs.	
Line of sight	Karytsas, S., O. Polyzou, and C. Karytsas, 2019: Social Aspects of Geothermal Energy in Greece. In: *Lecture Notes in Energy* [Manzella, A., A. Allansdottir, and A. Pellizzone, (eds.)]. Springer, Cham, Switzerland, pp. 123–144.	IEA, 2019: *Renewables 2019 – Analysis – IEA*. International Energy Agency, Paris, France, 204 pp.	
Energy storage for low-carbon grids	+	±	±
Role of context	General political acceptance and active promotion in the US, UK and Europe.	Given the concerns expressed about the competency of some communities and local authorities, there may well be a space for community, local government and private sector organisations to develop partnerships to deliver energy services in new, more flexible ways. It is not clear how such hybrid relationships may co-evolve with storage and other flexibility technologies over the longer term. Work is required on the markets.	The UK and Europe are exploring how to overcome these barriers and have been largely successful.
Line of sight	Imperial College London, Poyry (2017): ROADMAP FOR FLEXIBILITY SERVICES TO 2030 A report to the Committee on Climate Change Strachinescu, A. The Role Of The Storage In The Future European Energy System (2017); http://www.europeanenergyinnovation.eu/Articles/Spring-2017/The-role-of-the-storage-in-the-future-European-energy-system	Thomas, G., Demski, C., & Pidgeon, N. (2019). Deliberating the social acceptability of energy storage in the UK. Energy Policy, 133, 110908.	Strachinescu, A. The Role Of The Storage In The Future European Energy System (2017); http://www.europeanenergyinnovation.eu/Articles/Spring-2017/The-role-of-the-storage-in-the-future-European-energy-system
Demand-side mitigation	±	+	+
Role of context	Varies across mitigation options; less acceptable when options face public resistance.	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	Wolsink, M., 2020: Distributed energy systems as common goods: Socio-political acceptance of renewables in intelligent microgrids. *Renew. Sustain. Energy Rev.*, **127**, 109841, doi:10.1016/j.rser.2020.109841. Kuzemko, C., C. Mitchell, M. Lockwood, and R. Hoggett, 2017: Policies, politics and demand-side innovations: The untold story of Germany's energy transition. *Energy Res. Soc. Sci.*, **28**, 58–67, 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). Incentives are needed to align the market design with the 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). Incentives are needed to align the market design with the 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). Incentives are needed to align the market design with the low-carbon agenda. System integration can provide evidence in this regard.
Line of sight	Imperial College London, Poyry (2017): ROADMAP FOR FLEXIBILITY SERVICES TO 2030 A report to the Committee on Climate Change	Imperial College London, Poyry (2017): ROADMAP FOR FLEXIBILITY SERVICES TO 2030 A report to the Committee on Climate Change	Imperial College London, Poyry (2017): ROADMAP FOR FLEXIBILITY SERVICES TO 2030 A report to the Committee on Climate Change van Soest, H., 2018: Peer-to-peer electricity trading: A review of the legal context. *Compet. Regul. Netw. Ind.*, **19(3–4)**, 180–199, doi:10.1177/1783591719834902.