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Meta-analysis on necessary investment shifts to reach net zero pathways in Europe

In the format provided by the authors and unedited

Supplementary information:
Meta-analysis on necessary investment shifts to reach net zero pathways in Europe

Contents

The supplementary information includes:

- Supplementary text sections A-C
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A. Data and methods

This section provides additional information on the data and methods used for this article. It is divided into two sections of which the first describes supplementary information on the search process and the database compilation and the second specifies the analysis procedure.

Search process and database compilation

The literature search process included three steps as described in the methods section: the academic database search, the EU website search, and the web search. As described in the Methods section, the search process is based on a systematic application of inclusion criteria, which must all be met, and exclusion criteria, which lead to exclusion if even one applies. In a first step, documents are included if they 1) have a potential geographical focus on Europe (i.e, not stating an explicit focus on regions other than Europe), 2) are concerned with sectors or technologies that are in scope, and 3) have a forward-looking/technology-scaling focus. This decision is based on abstract screening (in the case of academic articles) or full-text screening (in the case of government documents or studies from IOs or industry because they usually do not provide an abstract). A fraction of the literature was screened independently by two researchers, to test the level of repeatability when applying the above-stated inclusion criteria. In a second step, we exclude documents that 1) do not focus on Europe, 2) do not cover all countries of the EU or at least 80% of our geographical scope (the EU plus the United Kingdom, Switzerland, and Norway) in terms of GDP as of 2020, and 3) do not provide explicit data on required future installed number/capacity, number/capacity additions, or investments.

Table S1 lists the keywords used for the structured search based on the academic database, Scopus.[1] Table S2 shows the subtopics on the "Climate section" section on the EU website[2] which we identified as relevant and, thus, screened for literature. Last, we conducted a semi-structured web search, which next to studies from international organizations (IOs) and industry, also identified four relevant academic (peer-reviewed) studies and seven relevant governmental reports. Figure S1 gives an overview of the systematic literature search process. In order to test the procedure of applying inclusion criteria, two reviewers independently screened 200 articles from the academic database search which corresponds to 10% of our starting base (n=1,897). This resulted in the same decision in 95% of the cases and large number of articles could be directly excluded due to the wrong geographical focus (e.g., ref[3] or ref[4]), different sectoral or technological foci (e.g., ref[5] or ref[6]) or a missing forward-looking/technology-scaling focus (e.g., ref[7] and ref[8]). In the next step, we read the full text and exclude articles that 1) do not focus on Europe, 2) do not cover all countries of the EU or at least 80% of our geographical scope in terms of GDP as of 2020, and 3) do not provide explicit data on required future installed number/capacity, number/capacity additions, or investments (see supplementary data – sheets: Academic database search; Governmental documents; web search).

Categories	List of keywords (stars indicate that diverse endings are possible)
Relevant infrastructure sector	energy system, electricity, power, grid infrastructure, T&D, transport* grid, transmission grid, distribution grid, transport*, charg*, infrastructure, charg* grid, rail, road, airport, building, heating, cooling, public lightning, infrastructure, port, inland waterway, metro, gas grid, oil, hydrogen, direct air capture, direct air carbon capture, BECCS, carbon capture and storage, coal, gas production
Investment/expansion focus	investment shift*, investment need*, investment requir*, financ* shift*, financ* need*, financ* requir*, fund*, shift*, fund* need*, fund* requir*, capacity addition*, capacity expansion*, cost-optimal, tranformation rate*
Climate/decarbonization focus	decarbon*, paris agreement, net zero, green deal, climate neutr*

Table S1 | Keywords used for academic database search via Scopus. Our Scopus string allowed for studies with publications date between 2016 and July 2021.

Subtopics classified as relevant	Subtopics classified as irrelevant
European Green Deal, Climate strategies & targets, Transport emissions, Funding for climate action, Adaption to climate change, European Climate Change Programme, Carbon capture, use and storage	EU Emissions Trading System (EU ETS), Efforts sharing: Member States' emission targets, Forests and agriculture, Protection of the ozone layer, Fluorinated greenhouse gases, Adaption to climate change, International action on climate change

Table S2 | Overview of subtopics on the EU website listed under "Climate Action".

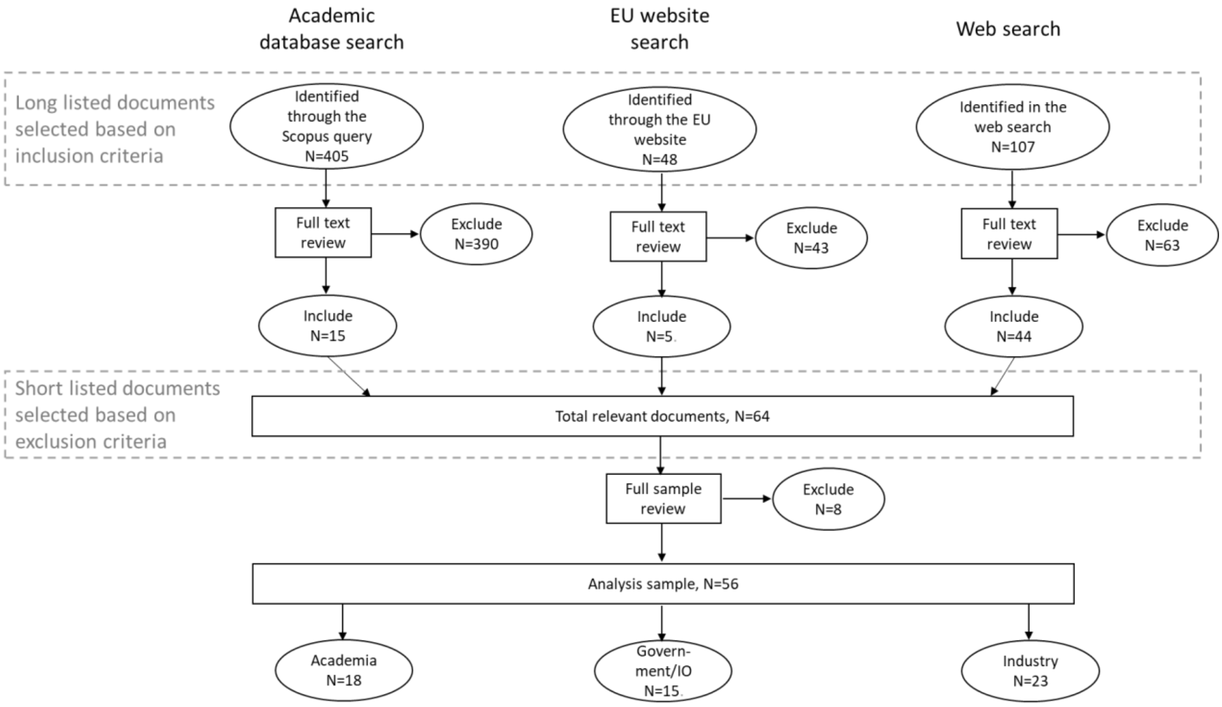

Figure S1 | Overview of the systematic literature search process

Considering the temporal distribution of the 56 studies identified in the search process as shown in Figure S2, we observe that the majority of the studies are from 2020 and 2021 although our structured search allowed for literature since 2016 and the semi-structured search did not impose a certain threshold for the publication year. Fewer studies in our literature base have been published between 2017 and 2019 and only one is from 2012. This rise in identified studies, specifically through the structured search approaches (academic database and EU website), indicates that the research coverage of studies, which fall in our scope, has increased over time and is likely to continue increasing. The cut-off date for the literature search of academic literature from Scopus was July 2021 and for studies from governments/IOs and industry end of 2021. However, we additionally included the latest IPCC report from 2022 – AR6 Climate Change: Mitigation on Climate Change – and its underlying scenario database because of its great relevance for climate mitigation research.

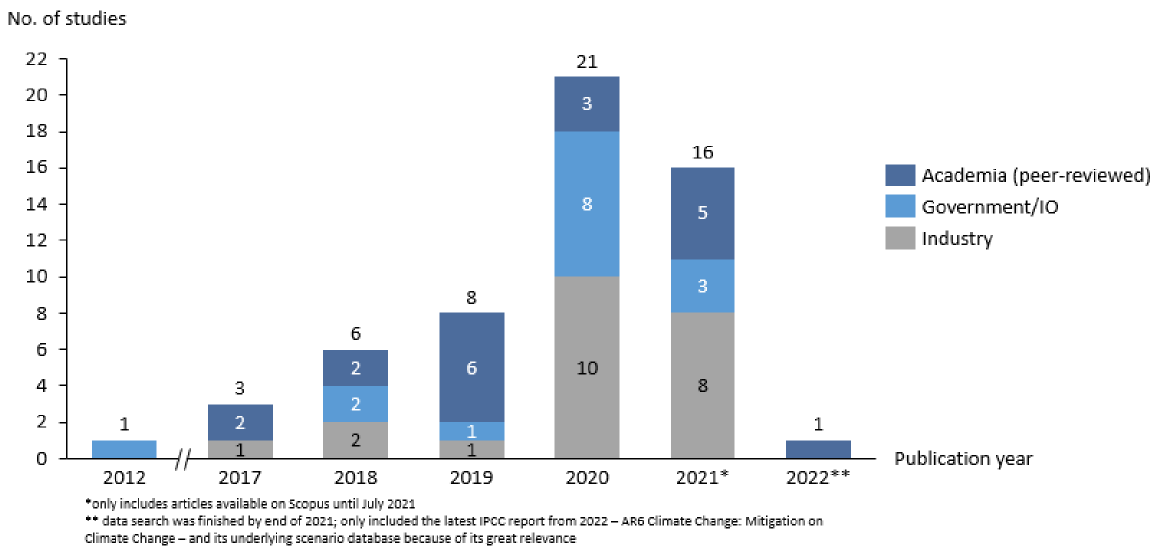

Figure S2 | Temporal distribution of publication year of the 56 studies in the final analysis sample

Table S3 gives an overview of our database by providing details for each study on the most important dimensions relevant for the subsequent meta-analysis. Our meta-analysis builds on data from 18 academic studies (peer-reviewed); 15 from governments or international organizations (IOs); and 23 from industry. Table S4 provides an additional breakdown of studies from industry into associations and consultancies. Considering the sector coverage, we see that none of the studies cover all sectors in the scope of this article. The vast majority of the studies focus on one or two distinctive sectors; only four studies cover five and one study covers six of the seven sectors in scope. In line with our findings on the research coverage, as shown by the numbers of time series per technology derived in our meta-analysis (see Figure 3 in the main article), we also observe here on the study level that power plants are well comparatively well covered with 28 studies. This also applies to "energy grids and storage", with 34 studies of which, however, 13 merely provide projections for electricity storage, which is often researched in combination with power plants. In terms of the type of projections, 35 studies provide non-monetary projections, 32 studies provide monetary projections and nine provide both. We also find projections on technology prices in 15 studies.

No.	**Reference** (in alphabetic order)	**Type of institution**			**Region covered**	**Sectors covered**							**Technologies covered**	**Type of projection**		**Scenarios considered**	**Type of scenario**	**Technology prices**	**Comments**
		Academia (peer-reviewed)	**Government/IO**	**Industry**		**Power plants (conevntional)**	**Power plants (renewable)**	**Energy networks & storage**	**CO2 networks & storage**	**Conventional fuel production**	**Low-carbon fuel production**	**Low-carbon transportinfrastructure**		**Monetary**	**Non-monetary**		***New EU target*** **(new) /** ***Baseline EU target*** **(bs)**		
1	Air Transport Action Group (2021)[9]			x	Europe + Armenia, Azerbaijan, Georgia						x		Synthetic gas/fuel	x		Pushing technology and operations, Aggressive SAF deployment, Aspirational technology perspective	New New New		
2	Artelys (2020)[10]			x	EU+ United Kingdom			x					Gas pipelines/grids/storage	x		High demand – Gas only, High demand – Integrated, On track – Gas only, On track – Integrated	Bs Bs Bs Bs		
3	Artelys (2020)[11]			x	EU			x					Electricity grids, Hydrogen pipelines/grids/storage	x		Unnamed scenario	New		Excluded (fragmented scope)
4	Boston Consulting Group (2021)[12]			x	EU + Iceland, Norway, Switzerland, United Kingdom							x	EV charging points		x	Unnamed scenario	Bs		
5	BloombergNEF (2020)[13]			x	EU + Norway, United Kingdom, Switzerland							x	EV charging points		x	Unnamed scenario	Bs	x	Data also available for power plants but on a too low ambition level
6	BloombergNEF (2021)[14]			x	EU + Norway, United Kingdom, Switzerland	x	x	x					Coal-fired, Gas-fired, Fossil – other (Oil-fired), Nuclear, Solar PV,		x	Current Policy Scenario, Ambitious Policy Scenario	Bs New	Same as in BloombergNEF 2020	

													Wind onshore Wind offshore Renewables other (biomass/gas, hydro, geothermal), Electricity storage (battery storage, hydro pumped storage)						
7	Bogdanov et al (2019)[15]	x			Europe excl. Belarus, Russia	x	x	x	x		x		Coal-fired, Gas-fired, Fossil – other (Oil-fired), Nuclear, Solar PV, Wind onshore Wind offshore Renewables – other (solar thermal, biomass/gas, hydro, geothermal), Electricity storage (battery storage, hydro pumped storage), CO2 networks & storage, Low-carbon hydrogen, Bio gas/fuel, Synthetic gas/fuel	x	x	Unnamed scenario	New	x	Some single data points excluded (frag-mented scope or not relevant for our scope)
8	Bogdanov et al (2021)[16]	x			Europe excl. Belarus, Russia	x	x	x	x		x		Coal-fired, Gas-fired, Fossil – other (Oil-fired), Nuclear, Solar PV, Wind onshore Wind offshore Renewables – other (solar thermal, biomass/gas, hydro, geothermal), Electricity storage (battery storage, hydro pumped storage), Gas pipelines/grids/storage District heating CO2 networks & storage, Low-carbon hydrogen, Bio gas/fuel, Synthetic gas/fuel	x	x	Unnamed scenario	New	x	Some single data points excluded (frag-mented scope or not relevant for our scope)
9	Byers et al (2022)[17]	x			EU + United Kingdom	x	x	x	x	x	x		Coal-fired, Gas-fired, Fossil – other (Oil-fired, fossil with CCS), Nuclear, Solar PV, Wind, Renewables – other (solar thermal, biomass/gas, biomass with CCS, hydro, geothermal),	x	x	IMAGE 3.0 – EN_INDCi2030_300f, AIM/CGE 2.2 – EN_Npi2020_900f, MESSAGEix-GLOBIOM_GEI 1.0 - SSP2_openres_lc_50, REMIND-MAgPIE 2.1-4.2 - SusDev_SDP-PkBudg1000, REMIND-MAgPIE 2.1-4.3 - DeepElec_SSP2_ HighRE_Budg900,	Bs, New, New, New, New, New	x	

													Electricity storage (battery storage, hydro pumped storage), CO2 networks & storage, Conventional fuel production, Low-carbon hydrogen, Bio gas/fuel			WITCH 5.0 - CO_Bridge			
10	Capgemini Invent (2020)[18]			x	EU			x				x	District heating EV charging points H2 refuelling stations	x		Unnamed scenario	New		Also covers energy sector but focused on single projects and therefore not com-parable to system-wide pro-jections
11	Community of European Railway and Infrastructure Companies (2021)[19]			x	EU							x	Rail infrastructure	x		Unnamed scenario	Undefined		
12	Deloitte Finance et al (2021)[20]			x	European Union + Norway, United Kingdom, Switzerland excl. 12Luxembourg, Cyprus				x		x		Hydrogen pipeline/grids/storage	x		Renewable push pathway, Technology Diversification pathway	New Bs	x	
13	Deloitte Monitor (2021)[21]			x	EU + United Kingdom (also for individual countries)			x					Electricity grids (distribution)	x		46% reduction ambition, 50-55% reduction ambition	New Bs		
14	DNV GL (2020)[22]			x	European Union + Norway, United Kingdom, Switzerland			x					Electricity grids (distribution, transmission), Gas pipelines/grids/storage, Hydrogen pipelines/grids/storage	x		1.5TECH (DNV GL style), Eurogas	New New		
15	Doll and Köhler (2018)[23]			x	European Union + Norway, United Kingdom, Switzerland							x	Rail infrastructure	x		Pro Rail	Undefined		
16	ECOFYS (2018)[24]			x	EU + United Kingdom			x	x				Electricity storage, Electricity grids (transmission), Gas pipelines/grids/storage,	x		Unnamed scenario	Bs		

													Oil pipelines/grids/storage, CO2 networks & storage,						
17	ENTSOG (2020)[25]			x	Europe + Azerbaijan, Georgia, Turkmenistan excl. Andorra, Belarus, Iceland, Kosovo, Luxembourg, Moldova, Montenegro, Norway, Russia, Serbia, Switzerland (also for individual countries)			x					Gas pipelines/grids/storage, Hydrogen pipelines/grids/storage,	x		Unnamed scenario	Bs		
18	ENTSOG and ENTSOE (2020)[26]			x	EU + United Kingdom	x	x	x			x		Coal-fired, Gas-fired, Fossil – other (Oil-fired, Fossil with CCS), Nuclear, Solar PV, Wind onshore, Wind offshore, Renewables other (solar thermal, hydro, other), Electricity storage (battery storage), Low-carbon hydrogen,		x	Distributed Energy, Global Ambition, National Trends	New New Bs		
19	European Commission (2018)[27]		x		EU + United Kingdom	x	x	x			x		Gas-fired, Fossil – other (Oil-fired, Fossil with CCS), Nuclear, Solar PV, Wind onshore, Wind offshore, Renewables – other (biomass with CCS, hydro, other), Electricity storage (battery storage, pumped hydro storage), Low-carbon hydrogen, Synthetic gas/fuel	x	x	1.5LIFE, 1.5TECH, CIRC, COMBO, EE, ELE, H2, P2X	New New Bs Bs Bs Bs Bs Bs		
20	European Commission (2019)[28]		x		EU + United Kingdom (also for individual countries)	x	x				x		Coal-fired, Gas-fired, Fossil – other (oil-fired, Fossil with CCS, thermal power), Nuclear, Solar PV,		x	EUCO3232.5	New		

													Wind, Renewables – other (biomass/gas, biomass with CCS, hydro, geothermal, other), Low-carbon hydrogen						
21	European Commission (2020)[29]		x		EU		x						Offshore wind, Renewable – other (ocean)		x	Unnamed scenario	New		
22	European Commission (2020)[30]		x		EU						x	x	Low-carbon hydrogen, H2 refuelling stations		x	Unnamed scenario	New	x	
23	European Commission (2020)[31]		x		EU	x	x	x			x		Fossil – other (Fossil with CCS), Nuclear, Solar PV, Wind onshore, Wind offshore, Renewables – other (biomass with CCS, hydro, other), Electricity storage (battery storage, pumped hydro storage), Electricity grids, Low-carbon hydrogen, Synthetic gas/fuel	x	x	Baseline, ALLBNK, CPRICE, MIX, MIX-50, REG	Bs New New New New New		
24	European Commission (2020)[32]		x		EU							x	H2 refuelling stations		x	Unnamed scenario	New		
25	European Commission (2020)[33]		x		EU + United Kingdom							x	Rail infrastructure	x		Unnamed scenario	Undefined		
26	European Commission (2021)[34]		x		EU	x	x	x			x		Gas-fired, Fossil – other (Fossil with CCS), Nuclear, Solar PV, Wind onshore, Wind offshore, Renewables other (biomass with CCS, hydro, other), Electricity storage (battery storage, pumped hydro storage), Electricity grids, Low-carbon fuels, Low-carbon hydrogen, Synthetic gas/fuel	x	x	REF, MIX, MIX-CP, REG,	Bs New New New		
27	European Commission (2021)[35]		x									x	EV charging points		x	Unnamed scenario	New		
28	Fuel Cells and Hydrogen 2			x	EU + United Kingdom			x			x	x	Hydrogen pipelines/grids/storage, Low-carbon hydrogen,	x	x	Ambitious scenario	New		

	Joint Undertaking (2019)[36]												H2 refuelling stations						
29	Gas for Climate (2020)[37]			x	EU + United Kingdom						x		Low-carbon hydrogen	x		Accelerated Decarbonisation Pathway	New		
30	Gas for Climate (2021)[38]			x	EU + United Kingdom, Switzerland excl. Bulgaria, Croatia, Cyprus, Latvia, Lithuania, Malta, Portugal, Rumania			x					Hydrogen pipelines/grids/storage		x	Low cost, Medium cost, High cost	Bs Bs Bs		
31	Global Infrastructure Hub (2021)[39]			x	Europe excl. Turkey							x	Rail infrastructure	x		Investment need inc. SDGs	Undefined		Also covers energy but only as aggre-gated sector
32	Hof et al. (2020)[40]	x			Europe excl. Belarus, Moldova, Russia, Turkey, Ukraine	x	x	x					Coal-fired, Gas-fired, Fossil – other (oil-fired, fFossil with CCS), Nuclear, Solar PV, Wind offshore, Wind onshore, Renewables – other (biomass/gas, biomass with CCS, solar thermal, hydro, other), Electricity storage (battery storage),		x	Broader regime change (witch) Technological substitution (witch)	Bs Bs		Two other models excluded because of outdated assumptions acc. to the authors
33	IEA (2020)[41]		x		Europe + Israel excl. Russia, EU + United Kingdom			x		x			Electricity storage (battery storage), Electricity grids (transmission, distribution), Oil pipelines/grids/storage, Hydrogen pipelines/grids/storage, Conventional fuel production	x		Stated policies scenario, Sustainable development scenario	Bs New		Also data on elec-tricity gene-ration but same basis as in IEA 2021
34	IEA (2020)[42]		x		Europe + Israel excl. Russia						x		Low-carbon hydrogen		x	Sustainable development scenario	New		
35	IEA (2021)[43]		x		Europe + Israel excl. Russia	x	x	x			x		Coal-fired, Gas-fired, Fossil – other (oil-fired, fossils with CCS), Nuclear, Solar PV,	x	x	Stated Policies Scenario, Announced Pledges Scenario, Sustainable Development Scenario	Bs New New	x	

													Wind, Renewables – other (hydro, other), Electricity storage (battery storage), Low-carbon hydrogen, Bio gas/fuel						
36	IRENA (2018)[44]		x		EU + United Kingdom	x	x						Coal-fired, Gas-fired, Fossil – other (oil-fired), Nuclear, Solar PV, Wind, Renewables – other (biomass, hydro, solar thermal, geothermal, other)		x	Remap	Bs		
37	IRENA (2020)[45]		x		EU + United Kingdom	x	x	x			x		Fossil, Renewables, Solar PV, Wind, Renewables – other (biomass), Electricity storage, Low-carbon hydrogen, Bio gas/fuel	x	x	Transforming Energy Scenario	Bs		
38	Knoblauch et al (2021)[46]	x			EU + United Kingdom			x					District heating	x	x	Scenario 1, Scenario 2, Scenario 3	Bs New New		Excluded (frag-mented scope)
39	Lorenz (2017)[47]	x			Europe excl. Belarus, Cyprus, Iceland, Malta, Moldova, Russia, Turkey, Ukraine	x	x	x					Coal-fired, Gas-fired, Nuclear, Solar PV, Wind offshore, Wind onshore, Renewables – other (biomass, hydro)		x	Unnamed scenario	New		
40	Lux and Pfluger (2021)[48]	x			Europe excl. Belarus, Cyprus, Iceland, Malta, Moldova, Russia, Turkey, Ukraine	x	x				x		Nuclear, Solar PV, Wind offshore, Wind onshore, Renewables – other (other), Low-carbon hydrogen		x	Unnamed scenario	New	x	
41	Mathiesen et al (2019)[49]	x[1]			EU + United Kingdom			x					District heating	x		Heat Roadmap Europe	New		
42	McCollum et al (2018)[50]	x			Europe excl. Belarus, Moldova, Russia, Ukraine	x	x	x		x	x		Fossil fuel plants, Renewable power plants, Electricity grids, Conventional fuel production,	x		Current Policies, Nationally Determined Contributions, Well Below 2 Degrees,	Bs Bs New New		

[1] Albeit the study is not peer reviewed we categorize it under Academia as it is based on a research project which has led to sevreal peer-reviewed papers and was conducted by the Aalborg University in Denmark which is an academic institution.

													Low-carbon hydrogen, Bio gas/fuel			Toward 1.5 Degrees			
43	McKinsey (2020)[51]			x	EU	x	x	x	x		x		Coal-fired, Gas-fired, Fossil – other, Nuclear, Solar PV, Wind offshore, Wind onshore, Renewables other (hydro, other), Electricity storage (battery storage), CO2 networks & storage, Bio gas/fuel		x	Cost-optimal	New	x	
44	OECD (2012)[52]		x		EU + United Kingdom							x	Rail infrastructure	x		Unnamed scenario	Undefined		
45	Paardekooper et al (2018)[53]	x			EU + United Kingdom (also for individual countries)			x					District heating	x		Conventionally decarbonised	Bs		
46	Persson et al (2019)[54]	x			EU + United Kingdom (also for individual countries)			x					District heating	x		Unnamed scenario	Bs		
47	Pietzker et al (2021)[55]	x			EU + Norway, United Kingdom, Switzerland	x	x	x			x		Coal-fired, Gas-fired, Fossil – other (gas with CCS), Nuclear, Solar PV, Wind offshore, Wind onshore, Renewables – other (biomass, biomass with CCS, hydro, solar thermal, other), Electricity storage (battery storage), Low-carbon hydrogen		x	Ambitious scenario, Reference scenario	New Bs	x	
48	Plessmann and Blechinger (2017)[56]	x			Europe excl. Belarus, Cyprus, Iceland, Malta, Moldova, Russia, Turkey, Ukraine	x	x	x			x		Coal-fired, Gas-fired, Nuclear, Solar PV, Wind, Electricity storage (battery storage, pumped hydro storage), Electricity grids (transmission), Synthetic gas/fuel	x	x	Unnamed scenario	Bs	x	
49	Ritter et al (2019)[57]	x			European Union + Norway, United Kingdom, Switzerland excl.	x	x	x			x		Gas-fired, Nuclear, Solar PV, Wind offshore,		x	Unnamed scenario	New		

					Cyprus, Malta (also for individual countries)								Wind onshore, Renewables – other (biomass, hydro) Electricity storage (battery storage, pumped hydro storage), Synthetic gas/fuel						
50	Tatarewicz et al (2021)[58]	x			EU + Norway, United Kingdom, Switzerland	x	x	x					Coal-fired, Gas-fired, Oil-fired, Fossil – other (Gas with CCS), Nuclear, Solar PV, Wind offshore, Wind onshore, Renewables – other (biomass, biomass with CCS, hydro) Electricity storage (pumped hydro storage, battery storage),		x	NEU NO BECCS	New New	x	
51	Transport & Environment (2020)[59]			x	EU + United Kingdom							x	EV charging points	x		Unnamed scenario	New	x	
52	Victoria et al (2020)[60]	x			EU + Norway, Bosnia and Herzegovina, Serbia, Switzerland United Kingdom excl. Cyprus, Malta	x	x	x			x		Coal-fired, Gas-fired, Nuclear, Solar PV, Wind offshore, Wind onshore, Renewables – other (biomass, hydro) Electricity storage (battery storage), Synthetic gas/fuel		x	Early and Steady Late and Rapid Early and Steady (incl. transport) Late and Rapid (incl. transport)	New New New New	x	
53	Weissbart (2020)[61]	x			EU + Norway, United Kingdom, Switzerland excl. Cyprus, Malta	x	x						Coal-fired, Gas-fired, Nuclear, Solar PV, Wind, Renewables – other (biomass, biomass with CCS, solar thermal, hydro)		x	Grand coalition Singleton coalition,	Bs Bs		
54	Wind Europe (2017)[62]			x	EU + Norway, United Kingdom, Switzerland		x						Wind onshore, Wind offshore		x	Low, Central, High	Bs Bs New		
55	Wind Europe (2019)[63]			x	EU + Norway, United Kingdom, Switzerland		x						Wind offshore		x	Unnamed scenario	New		
56	van Zuijlen et al (2019)[64]	x			Austria, Belgium, Denmark, France, Germany, Ireland,	x	x	x	x				Coal-fired, Gas-fired, Fossil – other (Gas with CCS),		x	Reference 70% IRES No CCS	Bs Bs Bs	x	Some single data

					Italy, Luxembourg, Netherland, Norway, Portugal, Spain, Sweden, Switzerland, United Kingdom,								Nuclear, Solar PV, Wind offshore, Wind onshore, Renewables – other (geothermal, biomass, biomass with CCS, hydro) Electricity storage (pumped hydro storage, battery storage), CO2 networks & storage			Low nuclear -1-1Gt	Bs New		points excluded (frag-mented scope or not relevant for our scope)

Table S3 | Overview of the database and the meta-data extracted from each study. Europe is defined as the European Union, Albania, Andorra, Belarus, Bosnia and Herzegovina, Iceland, Kosovo, Montenegro, Moldova, North Macedonia, Norway, Russia, Serbia, Switzerland, Turkey, Ukraine, and the United Kingdom.

Categorization of literature from industry	Studies included in the meta-analysis
Associations	Air Transport Action Group (2021)[9], Community of European Railway and Infrastructure Companies (2021)[19], ENTSOG (2020)[25], ENTSOG and ENTSOE (2020)[26], Fuel Cells and Hydrogen 2 Joint Undertaking (2019)[36], Gas for Climate (2020)[37], Gas for Climate (2021)[38], Transport & Environment (2020)[59], Wind Europe (2017)[62], Wind Europe (2019)[63]
Consultancies	Artelys (2020)[10], Artelys (2020)[11], Boston Consulting Group (2021)[12], BloombergNEF (2020)[13], BloombergNEF (2021)[14], Capgemini Invent (2020)[18], Deloitte Finance et al (2021)[20], Deloitte Monitor (2021)[21], DNV GL (2020)[22], ECOFYS (2018)[24], Global Infrastructure Hub (2021)[39], McKinsey (2020)[51]

Table S4 | Categorization of literature from other origins.

Analysis procedure

We extract the meta-data of the studies in a database format so that one entry (which is one line) refers to one technology-specific projection. For each line, we specify the corresponding information which includes the exact geographical scope, the scenario description (i.e., the underlying GHG emission reduction pathway), the variable specification (installed technology prices, and the projected installed/added capacity/number or investment) and the time horizon of the projection. While some studies provide average investment or expansion data over a longer time period, many studies provide 5-year averages as we do for this analysis. We extract the data on the same temporal granularity that is provided by the original study which results in multiple data entries for some technology-specific projections (if multiple time steps are provided) while for some studies only one entry per technology is extracted (if only one time step is provided). The entire database contains 4,837 entries and is provided in the supplementary data – sheet: database.

Technology classification:

To classify and group technology-specific projections, we define a technology classification based on the seven sectors that are within the scope (see Methods section). This classification includes three additional levels of detail, subsector, technology, and subtechnology, which are depicted in Table S5. This classification serves to categorize our variables of interest (i.e., future installed number/capacity, number/capacity additions, or investment) in our database into the technology classification (see supplementary data – sheet: database). We assign each entry to the technology classification shown in Table S5 which serves to aggregate all projections from the same study and scenario to the most detailed classification level (i.e., subtechnology). The results in the main article are shown on subsector and technology level. A breakdown on subtechnology level is provided in the supplementary data.

Sector	Subsector	Technology	Subtechnology
Power plants (conventional)	Fossil fuel plants	Coal-fired power plants	Coal-fired power plants
		Gas-fired power plants*	Gas-fired power plants
		Fossil – other	Oil-fired power plants
			Fossil power plants with CCS
	Nuclear power plants	Nuclear power plants	Nuclear power plants
Power plants (renewable)	Power plants (renewable)	Wind onshore*	Wind onshore
		Wind offshore*	Wind offshore
		Solar PV*	Solar PV
		Renewables – other(*)	Solar thermal
			Hydro
			Biomass/gas plant
			Biomass with CCS
			Multiple/other renewable (rest)
Energy networks & storage	Electricity grids	Electricity grids	Distribution grids*
			Transmission grids*
	Electricity storage	Electricity storage	Battery storage*
			Hydro pumped storage
	Gas pipeplines/grids/storage	Gas pipeplines/grids/storage	Gas pipeplines/grids/storage
	Hydrogen pipelines/grids/storage	Hydrogen pipelines/grids/storage	Hydrogen pipelines/grids/storage
	Oil pipelines/grids/storage	Oil pipelines/grids/storage	Oil pipelines/grids/storage
	District heating	District heating	District heating
CO2 networks & storage	CO2 networks & storage	CO2 networks & storage	CO2 networks & storage
Conventional fuel production	Conventional fuel production	Conventional fuel production	Conventional fuel production
Low-carbon fuels	Low-carbon hydrogen	Low-carbon hydrogen	Low-carbon hydrogen
	Bio gas/fuel	Bio gas/fuel	Bio gas/fuel
	Synthetic gas/fuel	Synthetic gas/fuel	Synthetic gas/fuel
Low-carbon transport infrastructure	Rail infrastructure	Rail infrastructure	Rail infrastructure
	EV charging points	EV charging points	EV charging points
	H2 refuelling stations	H2 refuelling stations	H2 refuelling stations

Table S5 | Sector and technology classification. The star-marked technology groups that must be covered to aggregate investment needs of a time series provided by a study for a specific scenario to the next higher aggregation level. The results in the main article are presented on subsector level (see Figure 1 in the main article) and technology level (see Figure 2-4 in the main article).

Data processing:

After the extraction of the raw data in a database structure, we process the data in multiple steps to receive a cleaned and harmonized dataset, which is suitable for use in calculating investment needs. First, we exclude projections that cannot be meaningfully included in our analysis, because they only cover fragmented parts of a technology category, as defined in our technology classification (e.g., projections that only focus on offshore grids and not the entire distribution or transmission grid system). Where additional information was needed, these exclusions are based on direct email exchanges with the authors of the studies or clear specifications within the study. Second, we exclude non-monetary figures (i.e., installed/added capacity/number) if monetary figures are provided at the same technology detail level for the same scenario from the same study. Third, if a study provides projections for the same scenario and technology but on two different geographical scopes (e.g., EU27 and Europe), we only consider the projections for the geographical scope that is closer to our defined geographical scope (the EU plus Norway, the United Kingdom, and Switzerland) in terms of GDP. Fourth, for non-monetary projections on battery storage, we exclude figures in power capacity (watts) if the study also provides figures in energy capacity (watthours) to acknowledge the importance of discharge duration for investment costs. Fifth and last, we aggregate all projections from the same study and scenario into our most detailed technology classification level (see Table S5 in SI) if there is a more detailed technology breakdown provided (see supplementary data – sheet: meta-analysis for which data have been merged). After we process the database along the five steps we obtain a cleaned database with 3,014 entries (see supplementary data – sheet: meta-analysis).

On the basis of this dataset, we convert, monetize and harmonize projections as described in the method section. We derive 628 technology-specific time series, of which 259 align with the *Baseline EU target*, 364 align with the *New EU target* and five remain undefined as they adhere to rail infrastructure.

Metrics and interpretation of investment needs

To consolidate and present the investment needs derived from our meta-analysis, we use and range of statistical metrics. All of them entail certain strengths and limitations which we describe below and which need to be considered in the interpretation of the results. We visualize all metrics in the main article using a range of approaches, such as boxplots, panel data, line charts tables. When describing the metrics, we refer to the corresponding visualisations in the article.

Mean

The mean is one of the most often used metrics in literature (e.g, ref[50] calculates the mean investment needs across models) and its concept is well known to a very broad audience. It captures the full range of data and also reflects the influence of extreme values. As the inclusion of extreme values represents the full picture of possible future pathways, we believe the mean to be a very informative metric for investors and policy-makers alike, specifically when being considered together with metrics less sensitive to outliers (i.e., median or interquartile range).

Median

The median represents the complement to the mean as it similarly attempts to derive a representative value of the underlying data. Still, it does not take into account extreme values by presenting the middle instead of the average of the data. Comparing results derived based on mean investment needs to results derived based on median investment needs helps to understand the influence of extreme values (see

Figure 1 and 2 in the main article as well as Figure S6 and S7). Consequently, we conduct a sensitivity analysis by using the median instead of the mean (see Figure S6 and S7).

Interquartile range

The interquartile range (IQR) represents the statistical dispersion of the data. It is defined as the difference between the 75th and 25th percentiles of the data. Equal to the median, the IQR is robust to outliers. Consequently, it is specifically informative in combination with the mean as it puts the influence of extreme values into context (see Figure 4 in the main article).

Standard deviation

The standard deviation (SD) is also a measure of the statistical dispersion of a data set. While a high standard deviation suggests that the values are dispersed over a wider range, a low standard deviation suggests that the values tend to be close to the mean of the data. The standard deviation is the square root of its variance. The variance is calculated by taking the average of the squared deviations of the individual values from the average value. As such, the standard deviation is more sensitive to outliers than the IQR. A useful characteristic of the standard deviation is that it is expressed in the same unit as the data as opposed to the variance (see Figure 4 in the main article).

Relative standard deviation

The relative standard deviation (RSD) indicates if the "absolute" standard deviation is a small or large quantity when compared to the mean of the data set. Thus, the RSD is particularly helpful to compare the dispersion of data across technologies with very different means. The RSD is calculated by dividing the "absolute" standard deviation by the mean and is expressed as a percentage (see Figure S5).

Additional information on extended analysis on the independence of Russian gas

To assess how future investment needs are affected by the EU's ambition to become independent from Russian gas (not reflected in the results of the main meta-analysis), we conduct an additional meta-analysis targeted to directly related studies only that have been published very recently.

Data collection

As the Russian invasion of Ukraine is less than half a year ago at the time of writing, we refrain from performing an extensive Scopus given the typical peer-review lead time. Instead, we resort to the two other channels used in the main meta-analysis: the EU website search and the semi-structured web search. For the governmental documents, we screen all documents on the EU website as of July 2022 listed as part of REPower EU page which is sorted under the broader European Green Deal section.[65] The screening procedure with the application of the inclusion criteria results in a long list of six articles, which is narrowed to a shortlist of one document after the full-text review and the application of the exclusion criteria.

We complement our literature base with a semi-structured web search for studies from IOs and industry, along the keywords "REPower EU", "Independence of Russian gas", and "Russian gas imports". The web search results in a long list of 14 and a shortlist of two documents. Additionally, we survey academics working in the field during June and July 2022, including via the German "Strommarktgruppe" which is an energy-focused email list from Europe with approximately 5,000 participants.[66] This results in a longlist of three and a shortlist of two documents.

Combining the short-listed documents from the EU website, the web search, and the survey of academics, we arrive at a total sample of five articles of which two are from academia, one from governments or IOs and two from industry (see supplementary data – sheet: Ex-analysis – Lit search for the full list of long-listed and short-listed studies).

Data analysis

Analogous to the main meta-analysis, we extract the meta-data on future investment needs/technology expansion and categorize them into our predefined technology classification (see Table S5). If needed, we convert total deployment to added deployment and monetize the projections using the average technology prices shown in Figure S4. In the next steps, we adjust for different time values of money using the HICP for the European Union to harmonize all technology prices to 2020 Euros and for different geographical scopes in accordance with the GDP as of 2020. For two studies, the projections are provided as a difference to the Fit for 55 measures (specified under the Green Deal) and in line with our *New EU target*. To make the three other studies comparable, we calculate the increase in addition to the level for the *New EU target* by taking the expansion/investment needs of the Fit for 55 measures as a baseline (see supplementary data – sheet: Ex analysis – RU gas phase out for more detailed information).

B. Supplementary information on the results

This section provides supplementary information on the results presented in the main article devided in four subsections. First, we assess investment needs in the relation to the gross domestic product (GDP). Second, we discuss the potential influence of the Covid pandemic on past investments. Third, we discuss the potential influence of different publication dates on the two targets and show details regarding the technology prices used. Fourth, we provide additional data and metrics on the dispersion of the future investment need estimates. Fifth, we investigate differences in investment need estimates by type of institution by showing percentage differences and p-values of t-tests.

Future investment needs in the context of future gross domestic product development

To contextualize the derived total investment needs (see Figure 1 in the main article) in light of future economic growth, we calculate their share of gross the gross domestic product (GDP) of our geographical scope. Table S6 shows historic infrastructure investments as well as future needs as a percentage of historic GDP and various GDP projections, respectively. For GDP projections, we resort to the five shared socioeconomic pathways (SSPs) which are also used as part of the IPCC Sixth Assessment Report. The SSPs describe scenarios of projected socioeconomic global changes, which are:

- SSP1: Sustainability (Taking the Green Road)[67]
- SSP2: Middle of the Road[68]
- SSP3: Regional Rivalry (A Rocky Road)[69]
- SSP4: Inequality (A Road divided)[70]
- SSP5: Fossil-fueled Development (Taking the Highway)[71]

2011-15	2016-20	*SSP*	2021-25	2026-30	2031-35
Baseline EU target					
1.54%	1.25%	***SSP1***	1.43%	1.37%	1.38%
		SSP2	1.45%	1.41%	1.44%
		SSP3	1.49%	1.49%	1.58%
		SSP4	1.45%	1.40%	1.42%
		SSP5	1.39%	1.29%	1.25%
New EU target					
1.54%	1.25%	***SSP1***	1.62%	1.62%	1.68%
		SSP2	1.64%	1.67%	1.76%
		SSP3	1.69%	1.76%	1.93%
		SSP4	1.64%	1.66%	1.73%
		SSP5	1.57%	1.53%	1.52%

Table S6 | Infrastructure investment needs as a percentage of GDP. Historic GDP is based on data from the International Monetary Fund database. GDP projections are based on the OECD Model for the five SSPs available in the IIASA database. All values are converted to standardized 2020 euros before calculating the shares.

We find that in the *Baseline EU target* the share of GDP (relative investment needs) increases in all five SSPs compared to the period of 2016-20 but remain below the level of 2011-15. In the *New EU target*, relative investment needs increase substantially compared to 2016-20 and also beyond the level of 2011-15 in all SSPs except for the later time periods in the fossil fuel development scenario (SSP5).

Influence of the Covid pandemic on past investments

As annual past investment levels of 2016–20 lie below past investment of 2011–15, we investigated whether the decline in annual investment over the second half of the previous decade was potentially driven by the global Covid pandemic. Figure S3 shows the development of total past investment from 2011 to 2020.

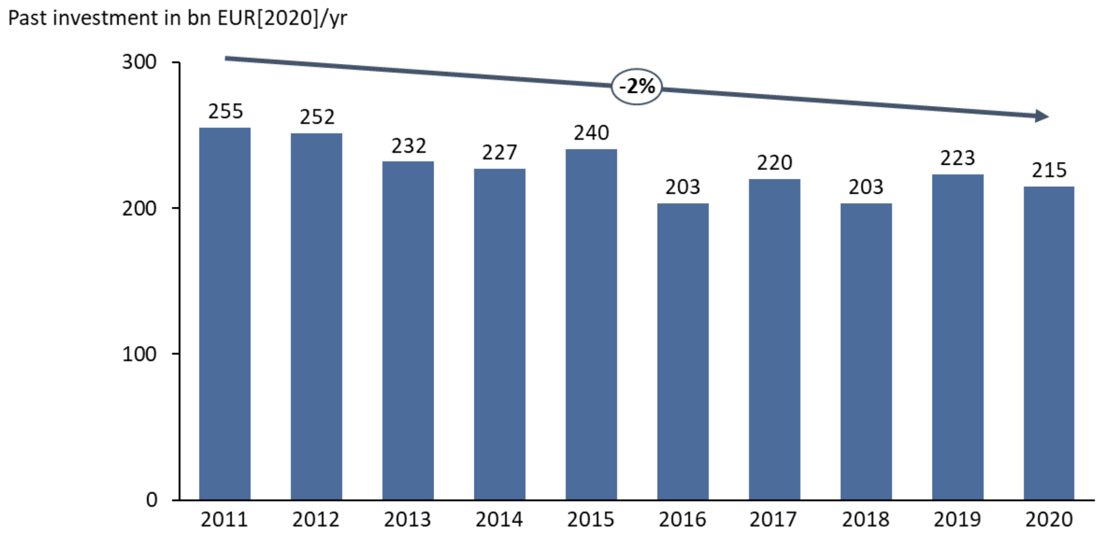

Figure S3 | Past investments for the energy and transport infrastructure in Europe. All underlying data points are harmonized to a common geographical scope, which is comprised of the EU, the United Kingdom, Switzerland, and Norway. Past investments are based on established data sources, such as the International Energy Agency, the International Renewable Energy Agency, and the Organization for Economic Co-operation and Development.

We observe a moderate decline in investment of EUR 8 bn in 2020, which is, however, within usual variations of previous years. Thus, the general downward trend which is observable does not seem to stem from the Covid pandemic and associated economic implications. Our analysis shows that the decline is largely driven by decreasing investment in renewable power plants, which declined from EUR 89 bn in 2011 to EUR 52 bn in 2020. At the same time, capacity expansion levels in 2020 were only 20% smaller than in 2011 which highlights the decrease in technology prices of renewable power plants.

Influence of bias from different publication dates on the two targets

With decreasing technology prices over time, it is likely that also projections of future technology prices in studies were increasingly adjusted downwards. Thus, we investigated whether the differences in our results for the *Baseline EU target* and the *New EU target* potentially stem from the fact that newer studies increasingly cover the *New EU target* and use more optimistic future technology price assumptions. This would lead to a systematic overestimation of our derived investment needs for the

Baseline EU target. Looking at the temporal distribution of the studies our database builds on, we see that this spans only a comparatively short time period (2017–2022, except for one study on rail infrastructure from 2012) with the vast majority published in 2020 and 2021. The temporal proximity of the two targets is also reflected in the average publication year over all time series which lies at 2019.3 and 2020.2 for the *Baseline EU target* and the *New EU target*, respectively. Thus, we consider such a bias from earlier publication to be rather limited. Also, the share of the type of institutions is fairly equal among the two scenarios, with 39%, 46%, and 15% in the *Baseline EU target* and 48%, 35%, and 17% in the *New EU target* from academia, governments/IOs and industry, respectively. This speaks for the comparability of the results of the two targets. Also, if monetary figures are not available (which is the case for two-thirds of our time series), we monetize technology expansion projections with average technology prices which we calculate based on data extracted from our literature base. For each technology group in our technology classification, we calculate time-specific technology prices by taking the average over prices per each time step. This results in technology-specific price projections provided in 5-year steps from 2010 to 2050. The time horizon of our analysis of future investment needs is 2035, and our analysis is comprised of three five-year periods (2021–25, 2026–30, and 2031–35). Figure S4 gives an overview of the average future technology prices over time for the technologies for which monetization is required. For additional context, we also show the minimum and maximum technology prices in our database. To further evaluate the influence of different technology prices, we conduct additional sensitivity analyses (see section C) by using non-monetary data for all studies that provide monetary as well as non-monetary data (instead of taking always monetary data if available) and by using the median instead of the mean technology prices to calculate future investment needs and shifts (see Figure S9 and S10).

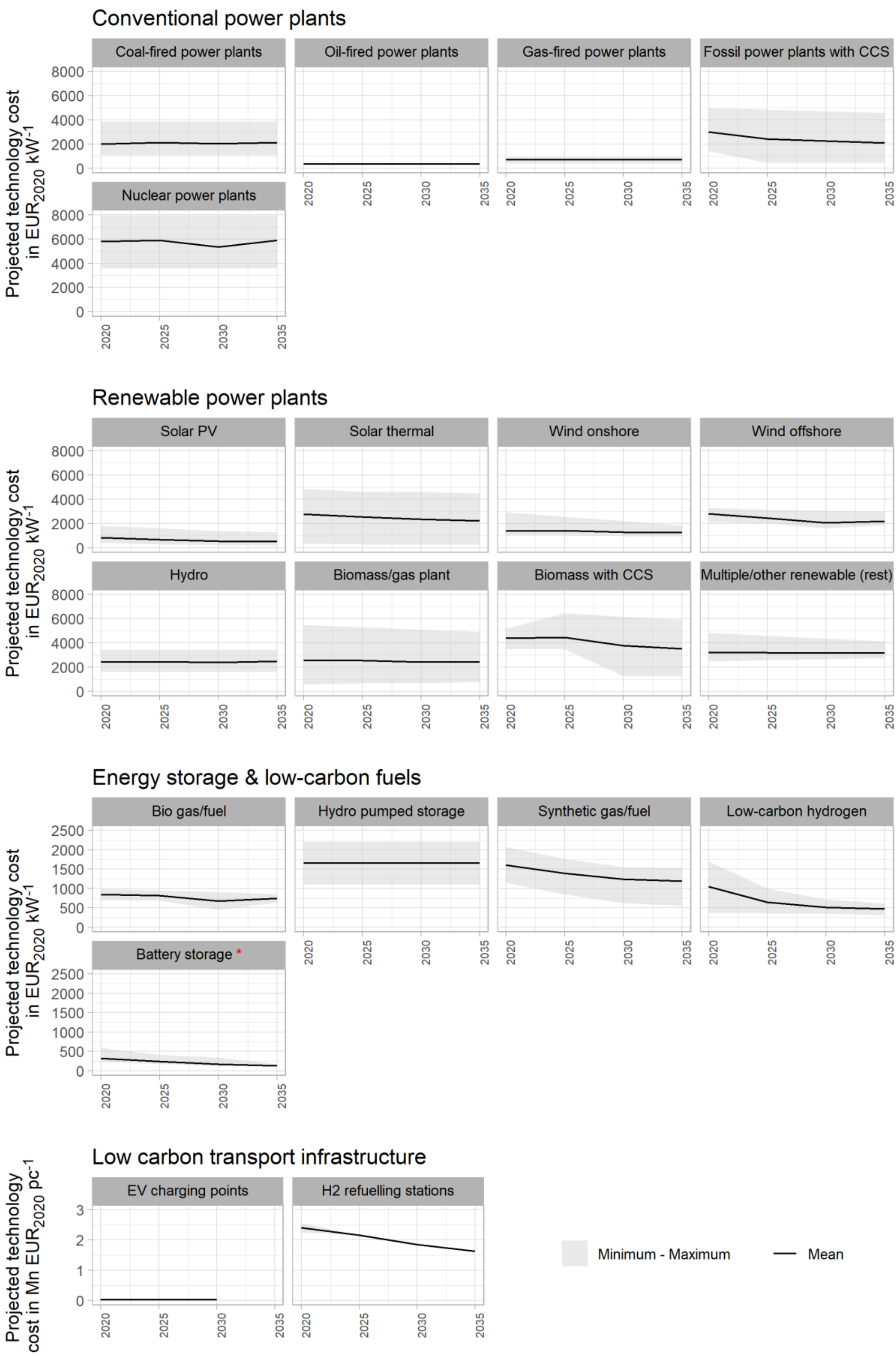

Figure S4 | Overview of mean, maximum and minimum technology prices from 2020-2035. Red star next to "Battery storage" indicates differing unit which is EUR_{2020} kWh^{-1}.

Further data on the variance of future investment projections

To provide additional data on the dispersion of future investment need projections, Table S7 provides a summary of the future investment projections by showing the mean, the median, the minimum, the maximum as well as the 1st and the 3rd quartile for both scenarios. To complement the picture, Figure S5 shows the absolute and relative standard deviation (SD) by technology and target. The relative standard deviation is calculated by dividing the absolute standard deviation by the mean. As such, the relative standard deviation indicates if the "absolute" standard deviation is a small or large quantity when compared to the mean (see methods in the main article for more information on metrics).

		Baseline EU target						New EU target					
	Period	Mean	Median	Min	Max	1st Quartile	3rd Quartile	Mean	Median	Min	Max	1st Quartile	3rd Quartile
Power plants (conventional)													
Nuclear power plants	2021-2025	€2.86	€0.00	€0.00	€24.11	€0.00	€0.01	€2.03	€0.00	€0.00	€17.14	€0.00	€0.00
Nuclear power plants	2026-2030	€3.40	€0.00	€0.00	€24.54	€0.00	€4.77	€2.84	€0.00	€0.00	€37.48	€0.00	€0.00
Nuclear power plants	2031-2035	€3.75	€0.84	€0.00	€22.33	€0.00	€5.88	€2.78	€0.00	€0.00	€17.85	€0.00	€0.00
Fossil fuel plants	2021-2025	€3.33	€0.36	€0.00	€13.05	€0.00	€7.34	€4.06	€2.80	€0.00	€19.32	€0.00	€5.82
Fossil fuel plants	2026-2030	€3.26	€0.85	€0.00	€11.12	€0.00	€6.90	€3.15	€2.86	€0.00	€9.01	€0.00	€5.53
Fossil fuel plants	2031-2035	€3.66	€0.66	€0.00	€14.28	€0.03	€7.30	€4.49	€3.84	€0.00	€24.79	€0.31	€6.68
Power plants (renewable)													
Renewable power plants	2021-2025	€51.96	€46.42	€8.82	€102.23	€42.65	€61.84	€74.48	€64.67	€4.11	€188.34	€57.48	€88.85
Renewable power plants	2026-2030	€52.56	€50.18	€10.24	€94.73	€40.28	€70.64	€89.50	€80.91	€12.09	€230.77	€57.32	€119.71
Renewable power plants	2031-2035	€51.62	€50.19	€12.97	€97.46	€32.53	€73.85	€96.88	€89.76	€20.07	€246.51	€69.80	€118.95
Energy networks & storage													
Oil pipelines/grids/storage	2021-2025	€0.34	€0.34	€0.16	€0.52	€0.16	€0.52	€0.40	€0.40	€0.40	€0.40	€0.40	€0.40
Oil pipelines/grids/storage	2026-2030	€0.28	€0.28	€0.03	€0.52	€0.03	€0.52	€0.40	€0.40	€0.40	€0.40	€0.40	€0.40
Oil pipelines/grids/storage	2031-2035	€0.28	€0.28	€0.03	€0.52	€0.03	€0.52	€0.40	€0.40	€0.40	€0.40	€0.40	€0.40
Hydrogen pipelines/grids/storage	2021-2025	€6.36	€3.03	€2.33	€19.55	€2.54	€4.38	€5.58	€1.10	€0.20	€17.82	€0.96	€7.81
Hydrogen pipelines/grids/storage	2026-2030	€6.27	€3.03	€2.04	€19.55	€2.33	€4.38	€5.58	€1.10	€0.20	€17.82	€0.96	€7.81
Hydrogen pipelines/grids/storage	2031-2035	€6.27	€3.03	€2.04	€19.55	€2.33	€4.38	€7.68	€6.20	€0.96	€17.82	€5.60	€7.81
Gas pipelines/grids/storage	2021-2025	€5.20	€0.35	€0.33	€13.04	€0.34	€11.02	€3.88	€2.10	€0.46	€10.86	€1.39	€4.59
Gas pipelines/grids/storage	2026-2030	€3.12	€0.35	€0.33	€13.04	€0.34	€3.72	€4.11	€2.10	€1.38	€10.86	€1.62	€4.59
Gas pipelines/grids/storage	2031-2035	€3.12	€0.35	€0.33	€13.04	€0.34	€3.72	€3.18	€0.89	€0.10	€10.86	€0.33	€3.75
District heating	2021-2025	€10.57	€10.57	€9.91	€11.23	€10.24	€10.90	€14.69	€13.86	€10.67	€19.55	€12.26	€16.70
District heating	2026-2030	€22.95	€22.95	€9.91	€36.00	€16.43	€29.48	€25.74	€10.67	€9.43	€57.14	€10.05	€33.90
District heating	2031-2035	€23.14	€23.14	€9.91	€36.37	€16.52	€29.75	€26.81	€13.80	€8.86	€57.78	€11.33	€35.79
Electricity grids	2021-2025	€54.07	€56.40	€18.41	€64.03	€49.84	€64.03	€61.31	€64.03	€20.61	€109.40	€51.29	€70.08
Electricity grids	2026-2030	€53.90	€56.40	€16.11	€64.03	€49.84	€64.03	€63.15	€64.03	€37.70	€109.40	€51.29	€70.08
Electricity grids	2031-2035	€71.47	€56.52	€31.93	€119.31	€49.84	€98.51	€74.61	€70.24	€38.96	€111.20	€51.29	€98.33
Electricity storage	2021-2025	€3.27	€3.03	€0.00	€5.95	€2.35	€4.62	€4.43	€2.51	€0.00	€28.98	€0.52	€5.61
Electricity storage	2026-2030	€2.59	€1.89	€0.00	€5.71	€1.89	€3.31	€5.74	€3.14	€0.00	€50.13	€1.89	€5.62
Electricity storage	2031-2035	€3.88	€2.98	€0.00	€10.93	€2.33	€5.10	€10.33	€4.11	€0.00	€66.06	€2.10	€9.47
CO2 networks & storage													
CO2 networks & storage	2021-2025	€0.04	€0.04	€0.00	€0.08	€0.02	€0.06	€1.27	€0.00	€0.00	€8.41	€0.00	€0.23
CO2 networks & storage	2026-2030	€0.08	€0.08	€0.05	€0.11	€0.07	€0.09	€1.42	€0.29	€0.00	€8.41	€0.17	€0.46
CO2 networks & storage	2031-2035	€0.18	€0.18	€0.11	€0.25	€0.14	€0.22	€3.93	€2.63	€0.00	€16.83	€0.52	€3.52
Conventional fuel production													
Conventional fuel production	2021-2025	€40.44	€42.15	€20.33	€57.13	€29.35	€53.23	€32.01	€28.82	€9.26	€64.40	€24.81	€35.18
Conventional fuel production	2026-2030	€40.40	€42.15	€20.16	€57.13	€29.31	€53.23	€25.69	€26.16	€3.53	€37.48	€23.61	€35.06
Conventional fuel production	2031-2035	€39.29	€42.15	€15.72	€57.13	€28.20	€53.23	€26.16	€26.06	€3.72	€45.47	€19.71	€35.06
Low-carbon fuel production													
Low-carbon hydrogen	2021-2025	€0.78	€0.16	€0.00	€6.09	€0.12	€0.70	€3.93	€1.74	€0.00	€29.61	€0.92	€3.90
Low-carbon hydrogen	2026-2030	€0.74	€0.10	€0.00	€6.09	€0.09	€0.69	€3.07	€1.07	€0.00	€19.02	€0.65	€3.54
Low-carbon hydrogen	2031-2035	€3.27	€1.57	€0.00	€12.99	€0.86	€2.86	€8.03	€4.60	€0.21	€19.02	€2.64	€14.63
Synthetic gas/fuel	2021-2025	€0.00	€0.00	€0.00	€0.00	€0.00	€0.00	€4.77	€0.57	€0.00	€39.86	€0.34	€2.21
Synthetic gas/fuel	2026-2030	€0.00	€0.00	€0.00	€0.00	€0.00	€0.00	€4.27	€0.50	€0.00	€34.53	€0.17	€2.13
Synthetic gas/fuel	2031-2035	€2.83	€0.00	€0.00	€15.25	€0.00	€1.99	€8.41	€8.19	€0.00	€30.68	€4.93	€9.64
Bio gas/fuel	2021-2025	€7.21	€7.46	€0.81	€11.58	€4.63	€11.58	€7.07	€3.74	€0.00	€19.84	€0.53	€13.72
Bio gas/fuel	2026-2030	€7.10	€7.46	€0.24	€11.58	€4.63	€11.58	€8.57	€9.36	€0.40	€19.84	€1.24	€14.41
Bio gas/fuel	2031-2035	€7.50	€7.46	€2.28	€11.58	€4.63	€11.58	€8.69	€9.80	€0.23	€19.84	€0.73	€14.62
Low-carbon transport infrastructure													
Rail infrastructure	2021-2025	€78.27	€74.56	€58.41	€101.94	€71.49	€84.93	€78.27	€74.56	€58.41	€101.94	€71.49	€84.93
Rail infrastructure	2026-2030	€81.77	€80.63	€58.41	€101.94	€71.49	€96.39	€81.77	€80.63	€58.41	€101.94	€71.49	€96.39
Rail infrastructure	2031-2035	€86.35	€88.68	€58.41	€111.23	€71.49	€101.94	€86.35	€88.68	€58.41	€111.23	€71.49	€101.94
EV charging points	2021-2025	€2.06	€2.06	€2.06	€2.06	€2.06	€2.06	€3.68	€3.09	€1.89	€6.63	€1.92	€4.85
EV charging points	2026-2030	€3.94	€3.94	€3.94	€3.94	€3.94	€3.94	€7.92	€4.99	€1.92	€19.75	€2.87	€10.04
EV charging points	2031-2035	€5.94	€5.94	€5.94	€5.94	€5.94	€5.94	€10.93	€7.35	€3.19	€25.83	€5.90	€12.38
H2 refuelling stations	2021-2025	NA	NA	NA	NA	NA	NA	€0.44	€0.46	€0.22	€0.62	€0.30	€0.61
H2 refuelling stations	2026-2030	NA	NA	NA	NA	NA	NA	€0.60	€0.46	€0.22	€1.25	€0.30	€0.76
H2 refuelling stations	2031-2035	NA	NA	NA	NA	NA	NA	€1.23	€1.18	€0.22	€2.35	€0.30	€2.12

Table S7 | Summary of future technology needs by subsector.

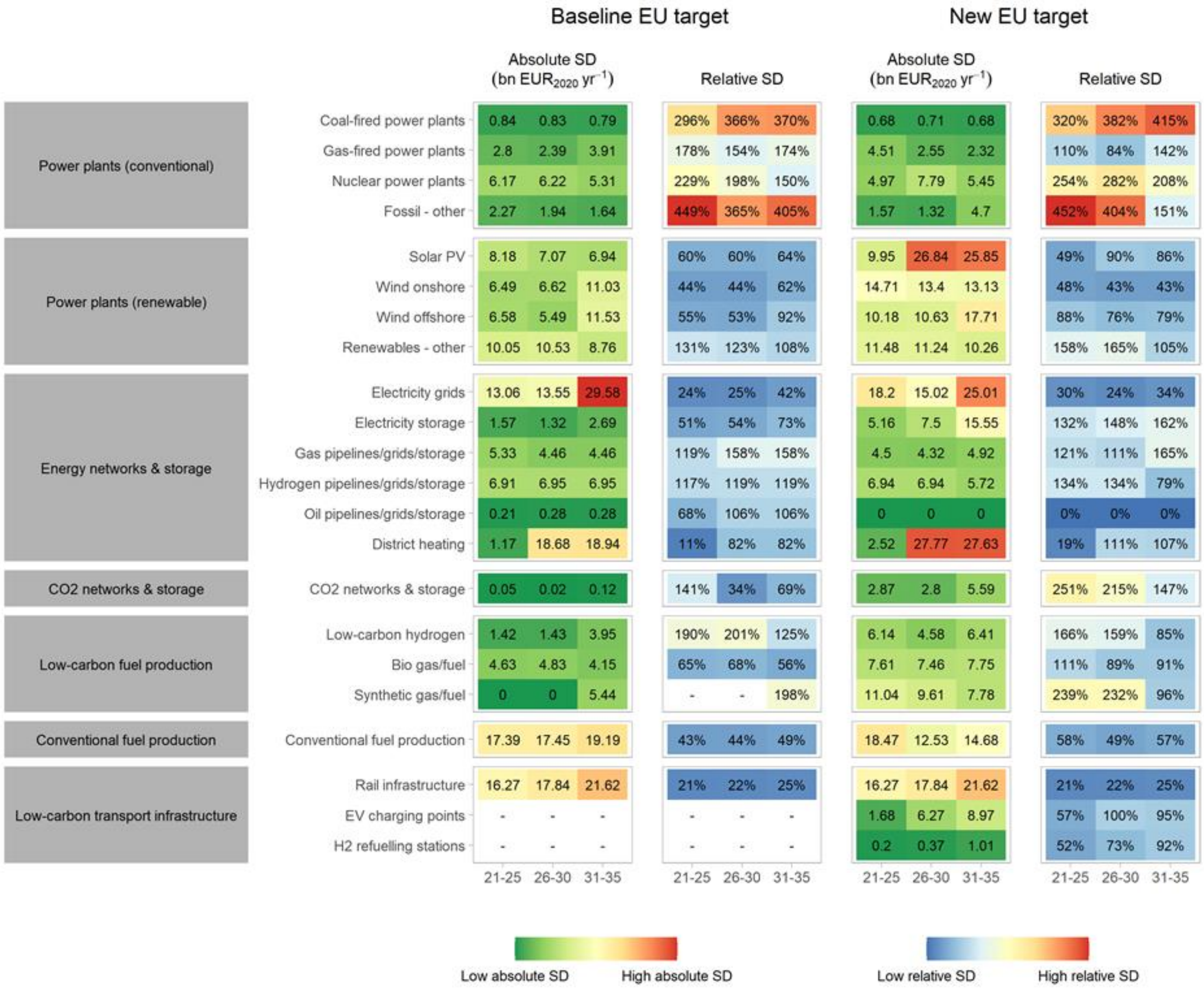

Figure S5 | Absolute and relative standard deviation (SD) by technology, time period and target.

Investigation of difference of investment need estimates by type of institution

To investigate differences in investment need estimates by type of institution, we split the time series for five key technologies into three groups: academia, government/international organization (IO) and industry. Table S8 indicates the investment need means for government/IO by technology, time period and target and how the means for academia and industry deviate (see Figure 5 in the main article for a graphical representation). Table S9 and S10 show the p-values for the t-tests conducted for which we describe the results in the main article.

		Baseline EU target			New EU target		
	Period	Government/ IO (mean)	Deviation - Academia	Deviation - Industry	Government/ IO (mean)	Deviation - Academia	Deviation - Industry
Power plants (renewable)							
Solar PV	2021-2025	€15.51	−12%	14%	€23.03	−3%	−25%
Solar PV	2026-2030	€12.81	−12%	68%	€19.12	133%	−20%
Solar PV	2031-2035	€11.39	−1%	23%	€21.41	98%	−18%
Wind offshore	2021-2025	€15.10	−47%	21%	€19.69	−85%	12%
Wind offshore	2026-2030	€12.18	−43%	38%	€17.15	−30%	12%
Wind offshore	2031-2035	€20.91	−73%	−58%	€31.42	−39%	−37%
Wind onshore	2021-2025	€15.58	1%	21%	€28.66	40%	−3%
Wind onshore	2026-2030	€17.10	−7%	−0%	€28.89	42%	−3%
Wind onshore	2031-2035	€20.24	1%	−35%	€44.11	−36%	−43%
Energy networks & storage							
Electricity grids	2021-2025	€57.97	−31%	NA	€63.96	−35%	43%
Electricity grids	2026-2030	€57.97	−33%	NA	€63.96	−22%	43%
Electricity grids	2031-2035	€78.89	−44%	NA	€82.51	−41%	2%
Electricity storage	2021-2025	€3.09	22%	−21%	€5.03	−11%	−41%
Electricity storage	2026-2030	€2.70	8%	−46%	€4.55	63%	−55%
Electricity storage	2031-2035	€3.73	21%	−30%	€3.84	312%	12%

Table S8 | Mean future investment needs for government/IO and deviation of means for academia and industry by time period and target for five key technologies.

P-values of T-tests comparing means of Government/IO to Industry

	Baseline EU target					New EU target				
	Solar PV	Onshore wind	Offshore wind	Electricity grids	Electricity storage	Solar PV	Onshore wind	Offshore wind	Electricity grids	Electricity storage
2021-2025	0.629	0.670	0.644	*NA*	0.687	0.128	0.873	0.718	0.369	0.060*
2026-2030	0.000***	0.999	0.389	*NA*	0.063*	0.194	0.860	0.651	0.369	0.005***
2031-2035	0.733	0.170	0.031**	*NA*	0.312	0.519	0.006***	0.037**	0.942	0.735

* $p<0.1$, ** $p<0.05$, *** $p<0.01$

Table S9 | P-values of t-tests comparing mean of time series from government/IO to mean from industry for each time point and target for five key technologies.

P-values of t-tests comparing means of Academic (peer-reviewed) to combined means of Government/IO and Industry

	Baseline EU target					New EU target				
	Solar PV	Onshore wind	Offshore wind	Electricity grids	Electricity storage	Solar PV	Onshore wind	Offshore wind	Electricity grids	Electricity storage
2021-2025	0.596	0.832	0.026**	0.227	0.295	0.850	0.117	0.000***	0.031**	0.976
2026-2030	0.429	0.762	0.031**	0.237	0.398	0.005***	0.049**	0.218	0.016**	0.291
2031-2035	0.873	0.715	0.009***	0.009***	0.482	0.014**	0.068*	0.282	0.000***	0.047**

* $p<0.1$, ** $p<0.05$, *** $p<0.01$

Table S10 | P-values of t-tests comparing mean of time series from academia to combined means from government/IO and industry for each time point and target for five key technologies.

C. Supplementary analyses

This section provides a range of sensitivity analyses to show how the results are affected by the statistical metrics used (e.g., mean vs median) and the approaches applied for monetizing and harmonizing the time series in the course of the meta-analysis (e.g., geographical scaling).

Sensitivity analysis 1: Median future investment needs

Figure S6 and S7 show the overall investment needs over the next 15 years as well as the investment shifts in the very near term when calculating median future investment needs. For most areas, investment trends remain the same compared to the main results (for which we used the mean). Still, future investment needs are smaller than in the main results albeit we also observe a considerable increase, specifically under the *New EU target*, leading to almost EUR 350 bn/yr in 2031–35. Looking at the subsector level, we find an even larger investment decline in conventional power plants but also fewer investments in renewable power plants. Still, the directions of the investment shifts (increase/decline) stay the same for both targets across all sectors and all technologies supporting the robustness our results.

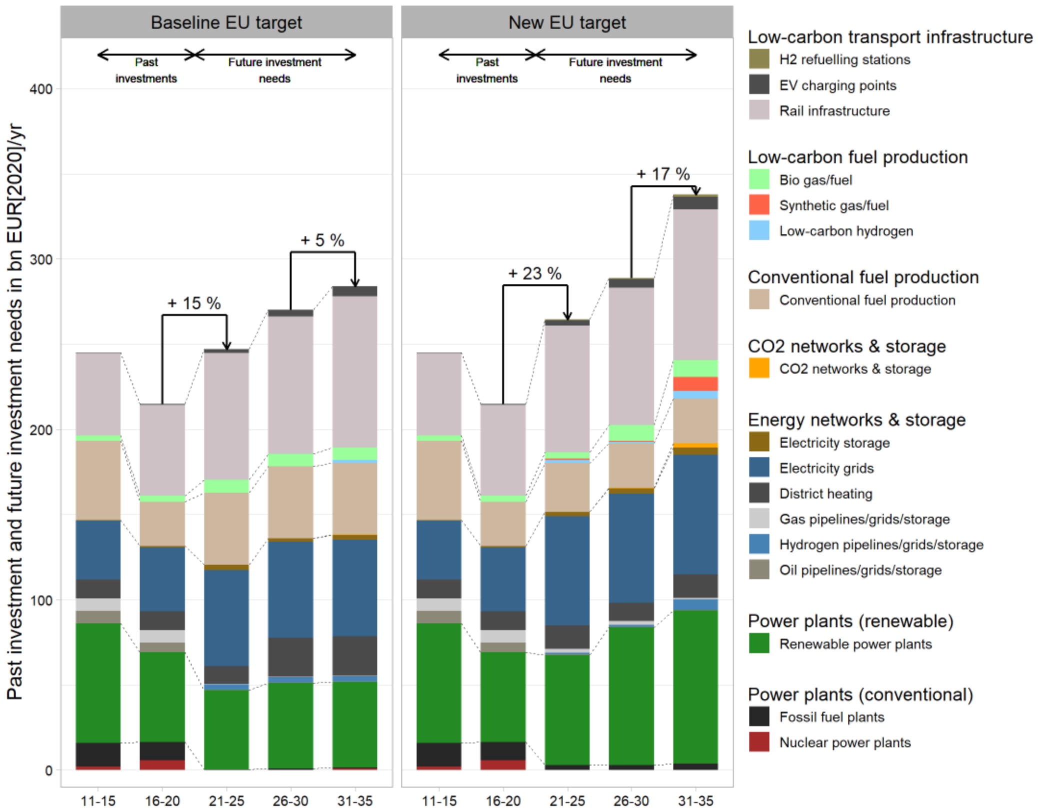

Figure S6 | Past investment and future investment needs for energy and transport infrastructure in Europe (median). The baseline EU GHG emissions reduction target refers to -40% by 2030 and -80% by 2050, while the new target refers to -55% by 2030 and -100% by 2050, all of which are below 1990 levels. All underlying data points are harmonized to a common geographical scope, which is comprised of the EU, the United Kingdom, Switzerland, and Norway. Past investments are based on established data sources, such as the International Energy Agency, the International Renewable Energy Agency, and the Organization for Economic Co-operation and Development. Future investment needs are represented as the median over all derived time series for the respective technology and period.

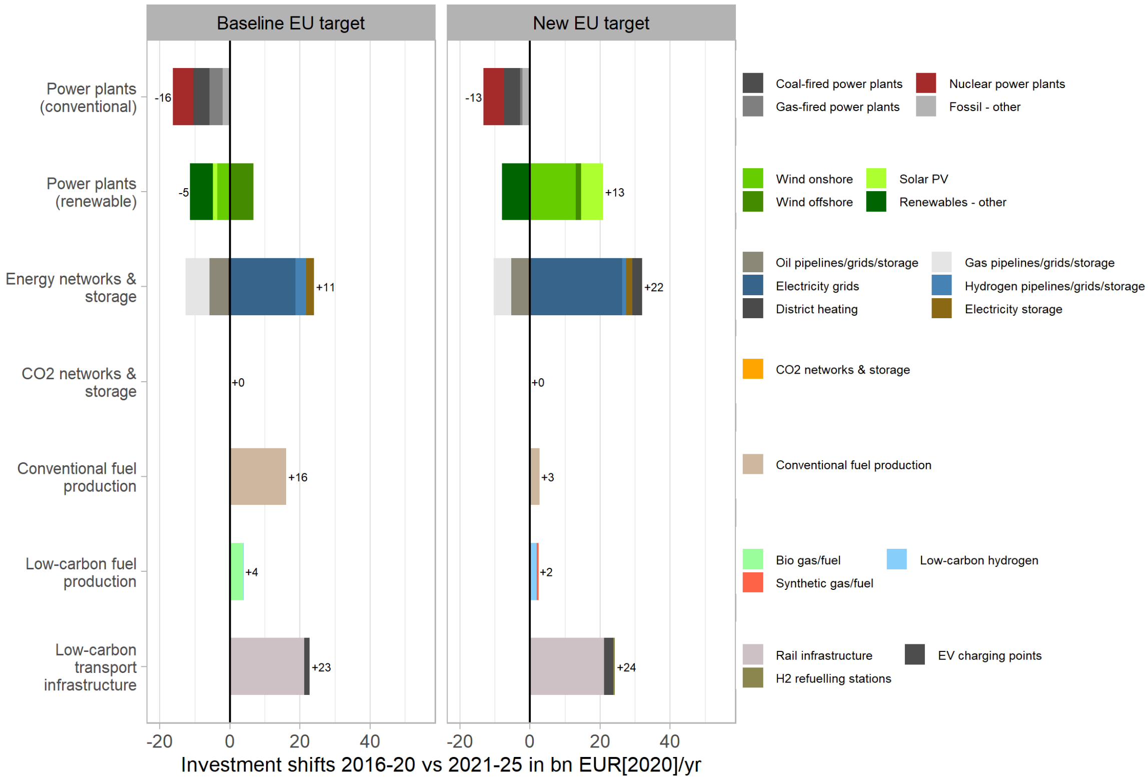

Figure S7 | Investment shifts required for Europe's energy and transport infrastructure between 2016–20 and 2021–25 (median). The baseline EU GHG emissions reduction target refers to -40% by 2030 and -80% by 2050, while the new target refers to -55% by 2030 and -100% by 2050, all of which are below 1990 levels. All underlying data points are harmonized to a common geographical scope, which is comprised of the EU, the United Kingdom, Switzerland, and Norway. Past investments (2016–20) are based on established data sources, such as the International Energy Agency, the International Renewable Energy Agency, and the Organization for Economic Co-operation and Development. Future investment needs (2021-25) are represented as the median over all derived time series for the respective technologies.

Sensitivity analysis 2: Minimum future investment needs (represented by 1st quartile)

Figure S8 shows the minimum investment needs over the next 15 years which we approximate by showing the 1st quartile of future investment need estimates. We observe that overall investment needs remain rather stable with a slight decline for the *Baseline EU target* and a slight increase for the *New EU target*. Looking at the subsector level, we see that the trends for increasing investment needs for electricity grids and rail infrastructure prevail while there is a decline for renewable power plants under both targets. One explanation could be differing assumptions for sector coupling activities across scenarios which leads to different levels of electrification.

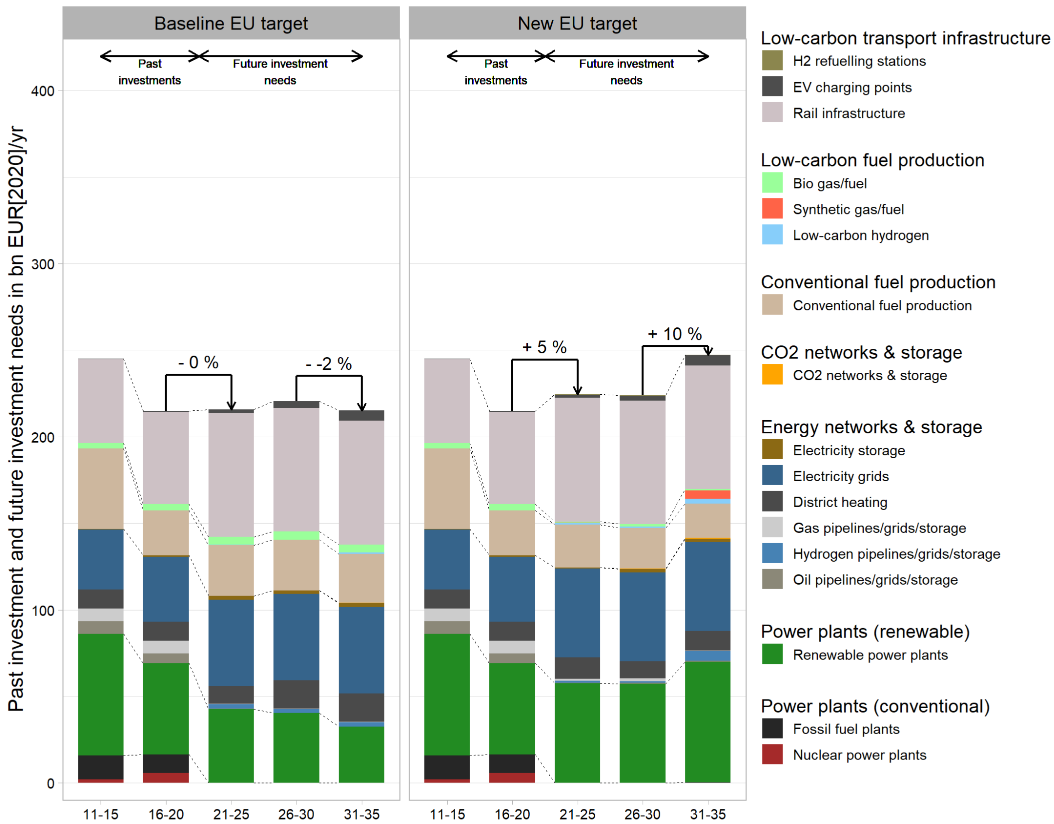

Figure S8 | Past investment and future investment needs for energy and transport infrastructure in Europe (1st quartile). The baseline EU GHG emissions reduction target refers to -40% by 2030 and -80% by 2050, while the new target refers to -55% by 2030 and -100% by 2050, all of which are below 1990 levels. All underlying data points are harmonized to a common geographical scope, which is comprised of the EU, the United Kingdom, Switzerland, and Norway. Past investments are based on established data sources, such as the International Energy Agency, the International Renewable Energy Agency, and the Organization for Economic Co-operation and Development. Future investment needs are represented as the median over all derived time series for the respective technology and period.

Sensitivity analysis 3: Maximum future investment needs (represented by 3rd quartile)

Figure S9 shows the maximum investment needs over the next 15 years which we approximate by showing the 3rd quartile of future investment need estimates. We observe that overall investment needs increase substantially in both scenarios and also stronger compared to when using the mean.

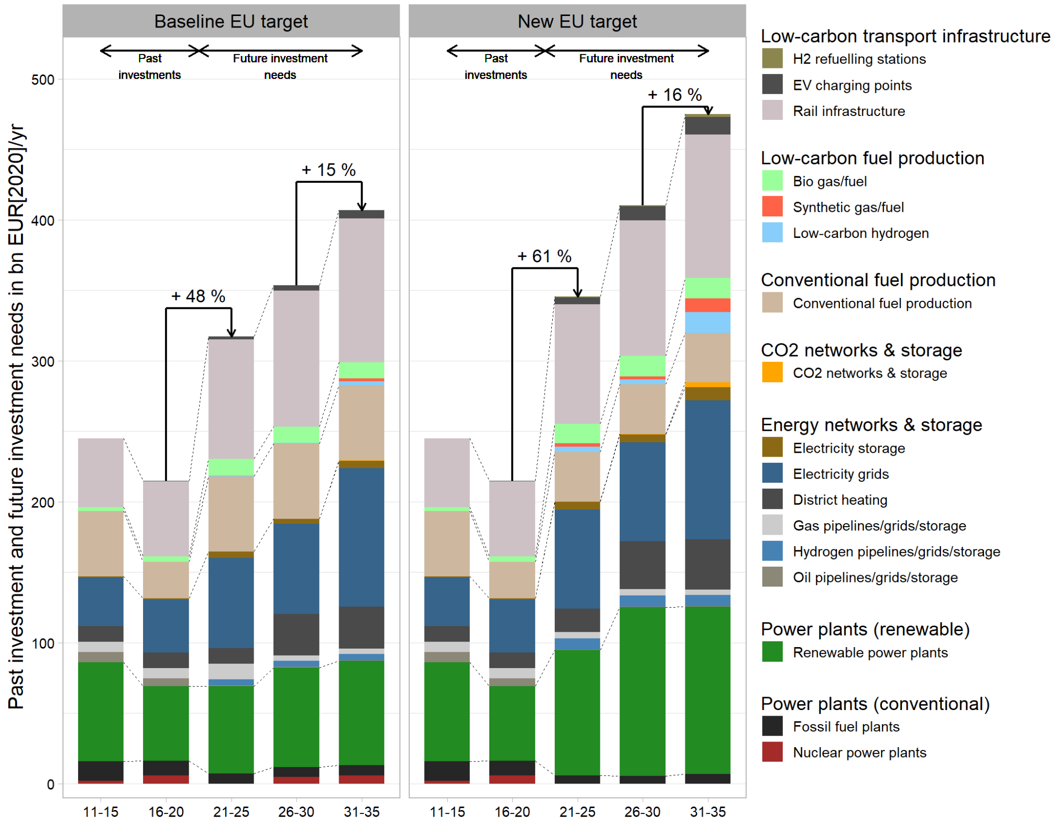

Figure S9 | Past investment and future investment needs for energy and transport infrastructure in Europe (3rd quartile). The baseline EU GHG emissions reduction target refers to -40% by 2030 and -80% by 2050, while the new target refers to -55% by 2030 and -100% by 2050, all of which are below 1990 levels. All underlying data points are harmonized to a common geographical scope, which is comprised of the EU, the United Kingdom, Switzerland, and Norway. Past investments are based on established data sources, such as the International Energy Agency, the International Renewable Energy Agency, and the Organization for Economic Co-operation and Development. Future investment needs are represented as the median over all derived time series for the respective technology and period.

Sensitivity analysis 4: Future investment needs with median technology prices

Figure S10 shows the investment needs over the next 15 years when monetizing non-monetary time series with median instead of mean technology prices. We observe very similar results for both targets compared to the main specification, speaking for the robustness of the results.

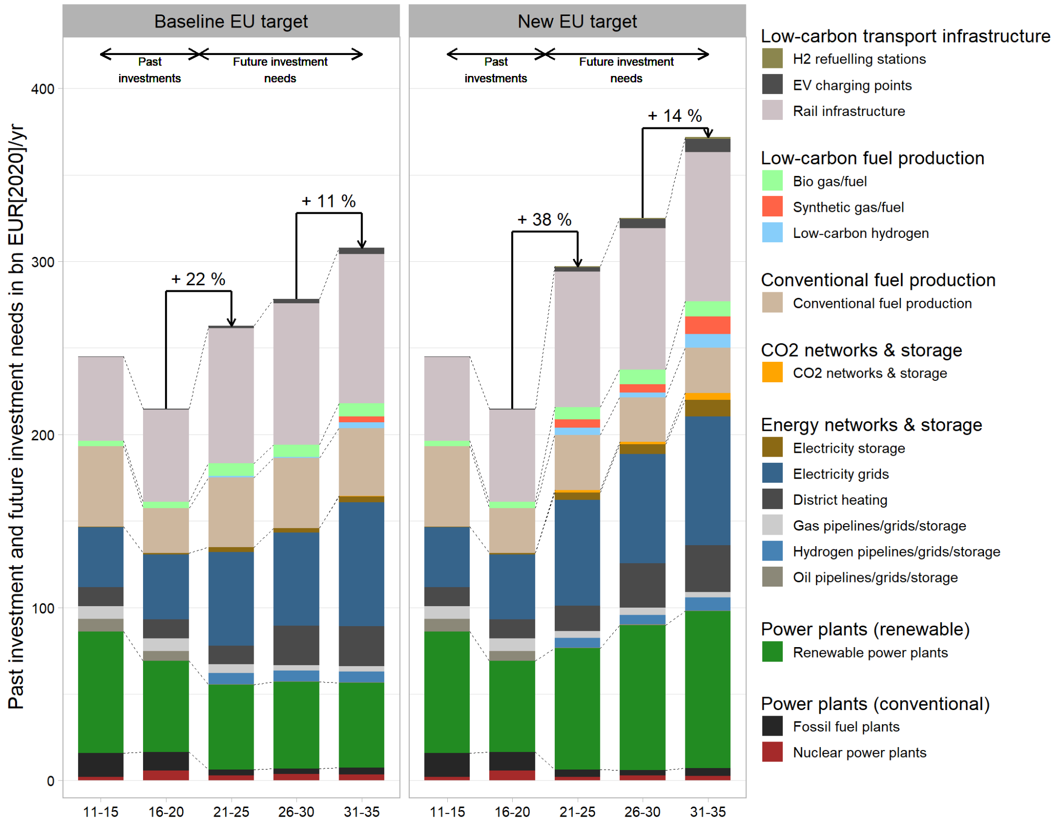

Figure S10 | Past investment and future investment needs for energy and transport infrastructure in Europe (technology prices – median). The baseline EU GHG emissions reduction target refers to -40% by 2030 and -80% by 2050, while the new target refers to -55% by 2030 and -100% by 2050, all of which are below 1990 levels. All underlying data points are harmonized to a common geographical scope, which is comprised of the EU, the United Kingdom, Switzerland, and Norway. Past investments are based on established data sources, such as the International Energy Agency, the International Renewable Energy Agency, and the Organization for Economic Co-operation and Development. Future investment needs are represented as the median over all derived time series for the respective technology and period.

Sensitivity analysis 5: Future investment needs with monetizing as preferred approach

While two-thirds of the 628 time series are only available in non-monetary format, one-third is directly provided in a monetary format. As we use monetary data whenever possible to derive the main results (see methods in the main article), we conduct a sensitivity by using non-monetary projections whenever available in addition to the monetary estimates. This is the case for one-quarter of all monetary data. Figure S11 shows future investment needs with monetization as the preferred approach. Overall, results remain very similar with a slight increase in investment needs for conventional and renewable power plants.

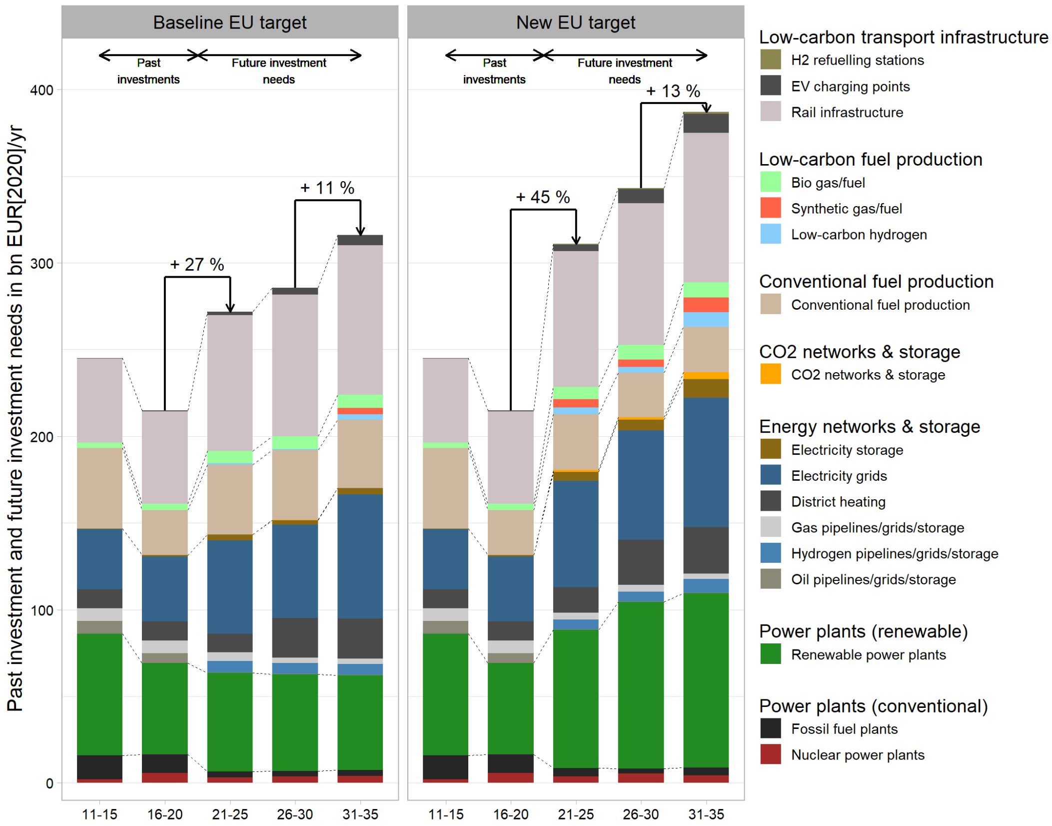

Figure S11 | Past investment and future investment needs for energy and transport infrastructure in Europe (monetizing as preferred approach). The baseline EU GHG emissions reduction target refers to -40% by 2030 and -80% by 2050, while the new target refers to -55% by 2030 and -100% by 2050, all of which are below 1990 levels. All underlying data points are harmonized to a common geographical scope, which is comprised of the EU, the United Kingdom, Switzerland, and Norway. Past investments are based on established data sources, such as the International Energy Agency, the International Renewable Energy Agency, and the Organization for Economic Co-operation and Development. Future investment needs are represented as the median over all derived time series for the respective technology and period.

Sensitivity analysis 6: Future investment needs with sectoral geographical harmonization

Since the exact geographical scope varies across the 56 studies in our database (albeit all focus on Europe or the EU in slight variations), we need to harmonize geographical scopes to our defined area (the EU + the United Kingdom, Switzerland, and Norway). We do so by scaling scopes in accordance with countries' GDP as of 2020 (see methods in the main article). We conduct a sensitivity analysis by scaling the geographical scopes with sectoral figures. For doing so, we use electricity production figures to scale power plants, electricity grids and storage investments; gas consumption to scale gas infrastructure, hydrogen infrastructure, CO2 infrastructure, district heating infrastructure and low-carbon fuels investments; and oil consumption to scale oil infrastructure investments. For low-carbon transport, we continue scaling with GDP as it is usually closely tied to transport spending. For conventional fuel production, we continue applying the past investment share of our defined geographical scope (the EU + the United Kingdom, Switzerland, and Norway) relative to the scope of the investment need projection to calculate an adjusted value as we do in the main specification. Figure S12 shows the results for the sectoral geographical harmonization, which leads to slightly lower, but very similar investment needs for both targets.

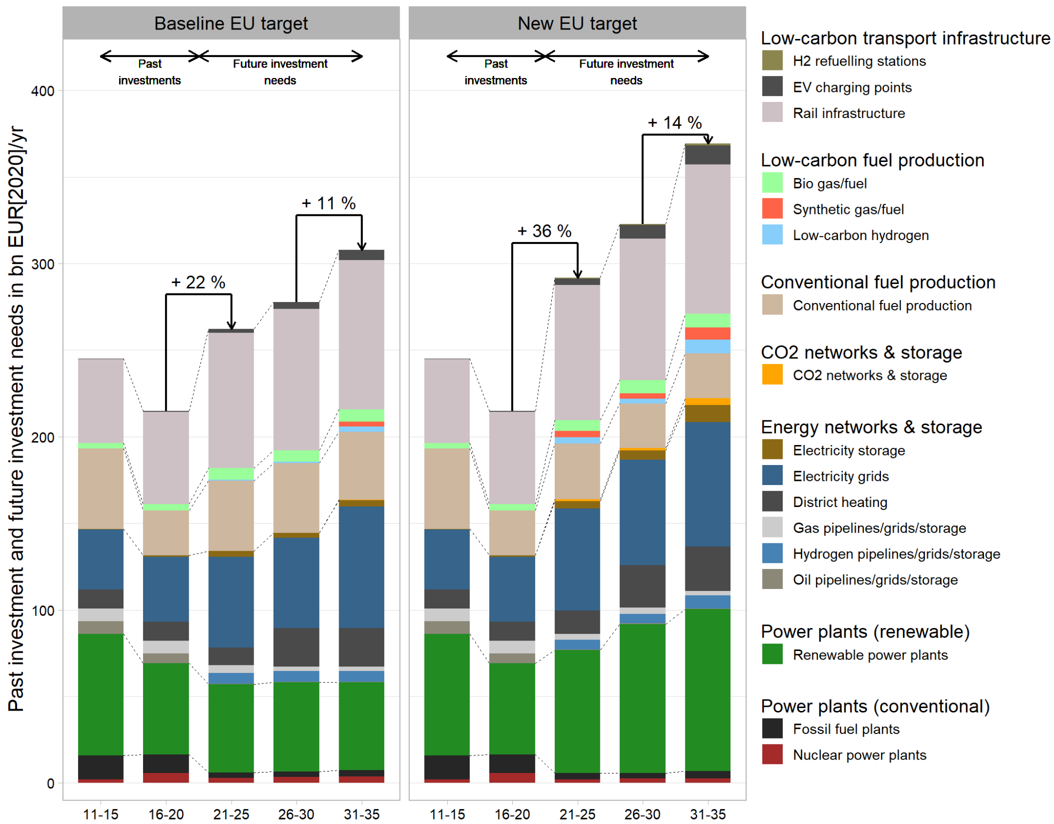

Figure S12 | Past investment and future investment needs for energy and transport infrastructure in Europe (sectoral geographical harmonization). The baseline EU GHG emissions reduction target refers to -40% by 2030 and -80% by 2050, while the new target refers to -55% by 2030 and -100% by 2050, all of which are below 1990 levels. All underlying data points are harmonized to a common geographical scope, which is comprised of the EU, the United Kingdom, Switzerland, and Norway. Past investments are based on established data sources, such as the International Energy Agency, the International Renewable Energy Agency, and the Organization for Economic Co-operation and Development. Future investment needs are represented as the median over all derived time series for the respective technology and period.

References

1. Elsevier. Scopus. Expertly curated abstract & citation database. Available at https://www.elsevier.com/solutions/scopus (2022).
2. European Commission. EU Action. Available at https://ec.europa.eu/clima/eu-action_en (2021).
3. Relva, S. G. *et al.* Enhancing developing countries' transition to a low-carbon electricity sector. *Energy* **220,** 119659 (2021).
4. Rodríguez-Sarasty, J. A., Debia, S. & Pineau, P.-O. Deep decarbonization in Northeastern North America: The value of electricity market integration and hydropower. *Energy Policy* **152,** 112210 (2021).
5. Li, C., Song, M., Zhang, Q. & Luo, Y. Cluster load based content distribution and speculative execution for geographically distributed cloud environment. *Computer Networks* **186,** 107807 (2021).
6. Huang, X., Zhang, J., Sresakoolchai, J. & Kaewunruen, S. Machine Learning Aided Design and Prediction of Environmentally Friendly Rubberised Concrete. *Sustainability* **13,** 1691 (2021).
7. Bravo, R., Ortiz, C., Chacartegui, R. & Friedrich, D. Multi-objective optimisation and guidelines for the design of dispatchable hybrid solar power plants with thermochemical energy storage. *Applied Energy* **282,** 116257 (2021).
8. Singh, K. & Hachem-Vermette, C. Economical energy resource planning to promote sustainable urban design. *Renewable and Sustainable Energy Reviews* **137,** 110619 (2021).
9. Air Transport Action Group. Waypoint 2050. Available at https://aviationbenefits.org/media/167417/w2050_v2021_27sept_full.pdf (2021).
10. Artelys. An updated analysis on gas supply security in the EU energy transition. Available at https://www.artelys.com/wp-content/uploads/2020/01/Artelys-GasSecurityOfSupply-UpdatedAnalysis.pdf (2020).
11. Artelys. What energy infrastructure to support 1.5°C scenarios? Available at https://www.artelys.com/wp-content/uploads/2020/12/Artelys-2050EnergyInfrastructureNeeds.pdf (2020).
12. Boston Consulting Group. Winning the battle in the EV charging ecosystem. Available at https://web-assets.bcg.com/55/e0/d244623746dba6826873121c4960/bcg-winning-the-battle-in-the-ev-charging-ecosystem-may-2021-r.pdf (2021).
13. BloombergNEF. New Energy Outlook 2020. Available at https://about.bnef.com/new-energy-outlook-2020/ (2020).

14. BloombergNEF. European Energy Transition Outlook. NEO Regional Scenarios. Available at (2021).

15. Bogdanov, D. *et al.* Radical transformation pathway towards sustainable electricity via evolutionary steps. *Nature communications* **10,** 1077 (2019).

16. Bogdanov, D. *et al.* Low-cost renewable electricity as the key driver of the global energy transition towards sustainability. *Energy* **227,** 120467 (2021).

17. Byers, E. *et al.* AR6 Scenarios Database. Available at https://zenodo.org/record/5886912#.YqCTc9pBw-U (2022).

18. Capgemini Invent. F I T FOR N E T- Z ERO : 55 Tech Quests to accelerate Europe's recovery and pave the way to climate neutrality. Available at https://www.capgemini.com/wp-content/uploads/2020/10/Net-zero-main-report-2020.pdf (2020).

19. Community of European Railway and Infrastructure Companies. CER comments to the EU Mobility Strategy. Available at https://www.cer.be/sites/default/files/publication/210420_CER_Comments%20to%20the%20EU%20Mobility%20Strategy.pdf (2021).

20. Deloitte Finance, IFPEN & SINTEF. Hydrogen4EU. Charting pathways to enable net zero. Available at https://2d214584-e7cb-4bc2-bea8-d8b7122be636.filesusr.com/ugd/2c85cf_69f4b1bd94c5439f9b1f87b55af46afd.pdf (2021).

21. Deloitte Monitor. Connecting the dots: Distribution grid investment to power the energy transition. Available at https://www2.deloitte.com/content/dam/Deloitte/ch/Documents/energy-resources/deloitte-ch-en-eurelectric-connecting-the-dots-study.pdf (2021).

22. DNV GL. European Carbon Neutrality: The Importance of Gas. A study for Eurogas. Available at https://eurogas.org/website/wp-content/uploads/2020/06/DNV-GL-Eurogas-Report-Reaching-European-Carbon-Neutrality-Full-Report.pdf (2020).

23. Doll, C. & Köhler, J. Reference and Pro Rail Scenarios for European Corridors to 2050. Working Paper 5 of the study LowCarb-RFC - European Rail Freight Corridors going Carbon Neutral. Fraunhofer ISI. Available at https://www.isi.fraunhofer.de/content/dam/isi/dokumente/sustainability-innovation/2018/WP15-2018_LowCarb_RFC_Rail-Scenarios.pdf (2018).

24. Ecofys. Investment needs in trans-European energy infrastructure up to 2030 and beyond. Final report. Available at http://publications.europa.eu/resource/cellar/431bc842-437c-11e8-a9f4-01aa75ed71a1.0001.01/DOC_1 (2018).

25. ENTSOG. TEN-YEAR NETWORK DEVELOPMENT PLAN. INFRASTRUCTURE REPORT. Available at https://www.entsog.eu/sites/default/files/2020-11/TYNDP2020_Infrastructure_Report%20_.pdf (2020).

26. ENTSOG & ENTSO-E. TYNDP 2020 Scenario Report. Available at https://eepublicdownloads.azureedge.net/tyndp-documents/TYNDP_2020_Joint_Scenario_Report_ENTSOG_ENTSOE_200629_Final.pdf (2020).

27. European Commission. IN-DEPTH ANALYSIS IN SUPPORT OF THE COMMISSION COMMUNICATION COM(2018) 773. A Clean Planet for all A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy. Available at (2018).

28. European Commission. Technical Note: Results of the EUCO3232.5 scenario on Member States. Available at https://ec.europa.eu/energy/sites/ener/files/technical_note_on_the_euco3232_final_14062019.pdf (2019).

29. European Commission. An EU Strategy to harness the potential of offshore renewable energy for a climate neutral future. Available at https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020DC0741&from=EN (2020).

30. European Commission. A hydrogen strategy for a climate-neutral Europe. Available at https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf (2020).

31. European Commission. COMMISSION STAFF WORKING DOCUMENT IMPACT ASSESSMENT Accompanying the document COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS. Stepping up Europe's 2030 climate ambition Investing in a climate-neutral future for the benefit of our people. Available at https://op.europa.eu/en/publication-detail/-/publication/749e04bb-f8c5-11ea-991b-01aa75ed71a1/language-en/format-PDF/source-215296770 (2020).

32. European Commission. Sustainable and Smart Mobility Strategy – putting European transport on track for the future. Available at https://eur-lex.europa.eu/resource.html?uri=cellar:5e601657-3b06-11eb-b27b-01aa75ed71a1.0001.02/DOC_1&format=PDF (2020).

33. European Commission. COMMISSION STAFF WORKING DOCUMENT Accompanying the document COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS Sustainable and Smart Mobility Strategy – putting European transport on track for the future. Available at https://op.europa.eu/en/publication-detail/-/publication/6ea435f8-3b06-11eb-b27b-01aa75ed71a1/language-en/format-PDF/source-222354170 (2020).

34. European Commission. Proposal for a DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL amending Directive (EU) 2018/2001 of the European Parliament and of the Council, Regulation (EU) 2018/1999 of the European Parliament and of the Council and Directive 98/70/EC of the European Parliament and of the Council as regards the promotion of energy from renewable sources, and repealing Council Directive (EU) 2015/652. Available at https://ec.europa.eu/info/sites/default/files/amendment-renewable-energy-directive-2030-climate-target-with-annexes_en.pdf (2021).

35. European Commission. Make Transport Greener. Available at https://op.europa.eu/en/publication-detail/-/publication/149507b6-00e3-11ec-8f47-01aa75ed71a1 (2021).

36. Fuel Cells and Hydrogen 2 Joint Undertaking. Hydrogen roadmap Europe. A sustainable pathway for the European energy transition. Available at https://www.fch.europa.eu/sites/default/files/Hydrogen%20Roadmap%20Europe_Report.pdf (2019).

37. Gas for Climate. Gas Decarbonisation Pathways 2020–2050. Available at https://gasforclimate2050.eu/wp-content/uploads/2020/04/Gas-for-Climate-Gas-Decarbonisation-Pathways-2020-2050.pdf (2020).

38. Gas for Climate. Extending the European Hydrogen Backbone. A EUROPEAN HYDROGEN INFRASTRUCTURE VISION COVERING 21 COUNTRIES. Available at (2021).

39. Global Infrastructure Hub. Global Infrastructure Outlook. Available at https://cdn.gihub.org/outlook/live/methodology/Global+Infrastructure+Outlook+-+July+2017.pdf (2017).

40. Hof, A. F. *et al.* From global to national scenarios: Bridging different models to explore power generation decarbonisation based on insights from socio-technical transition case studies. *Technological Forecasting and Social Change* **151,** 119882 (2020).

41. IEA. World Energy Outlook 2020. Available at (2020).

42. IEA. Energy Technology Perspectives 2020. Available at https://iea.blob.core.windows.net/assets/7f8aed40-89af-4348-be19-c8a67df0b9ea/Energy_Technology_Perspectives_2020_PDF.pdf (2020).

43. IEA. World Energy Outlook 2021. Available at https://iea.blob.core.windows.net/assets/4ed140c1-c3f3-4fd9-acae-789a4e14a23c/WorldEnergyOutlook2021.pdf (2021).

44. IRENA. Renewable energy prospects for the European Union: Preview for policy makers. Available at https://www.irena.org/publications/2018/Feb/Renewable-energy-prospects-for-the-EU (2018).

45. International Renewable Energy Agency (IRENA). Global Renewables Outlook: Energy Transformation 2050. Available at https://www.irena.org/publications/2020/Apr/Global-Renewables-Outlook-2020 (2020).

46. Knobloch, F. *et al.* FTT:Heat — A simulation model for technological change in the European residential heating sector. *Energy Policy* **153,** 112249 (2021).

47. Lorenz, C. Balancing reserves within a decabonized European electricity System in 2050 — From market developments to model insights. In *2017 14th International Conference on the European Energy Market (EEM)* (2017), pp. 1–8.

48. Lux, B. & Pfluger, B. A supply curve of electricity-based hydrogen in a decarbonized European energy system in 2050. *Applied Energy* **269,** 115011 (2020).

49. Mathiesen, B. V. *et al.* Towards a decarbonised heating and cooling sector in Europe. Unlocking the potential of energy efficiency and district energy. Available at http://www.districtenergyinitiative.org/sites/default/files/publications/towardsadecarbonisedhcsectorineufinalreport-111220191046.pdf (2019).

50. McCollum, D. L. *et al.* Energy investment needs for fulfilling the Paris Agreement and achieving the Sustainable Development Goals. *Nature Energy* **3,** 589–599 (2018).

51. McKinsey & Company. Europe Net-Zero Decarbonization pathways and socioeconomic implications. Available at https://www.mckinsey.com/business-functions/sustainability/our-insights/how-the-european-union-could-achieve-net-zero-emissions-at-net-zero-cost (2020).

52. OECD. Strategic Transport Infrastructure Needs to 2030. Available at https://www.oecd-ilibrary.org/docserver/9789264114425-en.pdf?expires=1647108962&id=id&accname=ocid72024074a&checksum=8B7C0D4E3AA2A6A63A23D56740D9F838 (2012).

53. Paardekooper *et al.* Heat Roadmap Europe Quantifying the Impact of Low-carbon Heating and Cooling Roadmaps. Aalborg Universitetsforlag. Available at https://vbn.aau.dk/ws/portalfiles/portal/288075507/Heat_Roadmap_Europe_4_Quantifying_the_Impact_of_Low_Carbon_Heating_and_Cooling_Roadmaps.pdf (2018).

54. Persson, U., Wiechers, E., Möller, B. & Werner, S. Heat Roadmap Europe: Heat distribution costs. *Energy* **176,** 604–622 (2019).

55. Pietzcker, R. C., Osorio, S. & Rodrigues, R. Tightening EU ETS targets in line with the European Green Deal: Impacts on the decarbonization of the EU power sector. *Applied Energy* **293,** 116914 (2021).

56. Pleßmann, G. & Blechinger, P. How to meet EU GHG emission reduction targets? A model based decarbonization pathway for Europe's electricity supply system until 2050. *Energy Strategy Reviews* **15,** 19–32 (2017).

57. Ritter *et al.* Effects of a Delayed Expansion of Interconnector Capacities in a High RES-E European Electricity System. *Energies* **12,** 3098 (2019).

58. Tatarewicz, I. *et al.* The Role of BECCS in Achieving Climate Neutrality in the European Union. *Energies* **14,** 7842 (2021).

59. Transport & Environment. Recharge EU: EU public charging infrastructure needs until 2030. Available at https://www.transportenvironment.org/wp-content/uploads/2021/07/01%202020%20Draft%20TE%20Infrastructure%20Report%20Final.pdf (2020).

60. Victoria, M., Zhu, K., Brown, T., Andresen, G. B. & Greiner, M. Early decarbonisation of the European energy system pays off. *Nat Commun* **11,** 6223 (2020).

61. Weissbart, C. Decarbonization of power markets under stability and fairness: Do they influence efficiency? *Energy Economics* **85,** 104408 (2020).

62. WindEurope. Wind energy in Europe: Scenarios for 2030. Available at https://windeurope.org/wp-content/uploads/files/about-wind/reports/Wind-energy-in-Europe-Scenarios-for-2030.pdf (2017).

63. WindEurope. Our energy, our future. How offshore wind will help Europe go carbon-neutral. Available at https://windeurope.org/wp-content/uploads/files/about-wind/reports/WindEurope-Our-Energy-Our-Future.pdf (2019).

64. van Zuijlen, B., Zappa, W., Turkenburg, W., van der Schrier, G. & van den Broek, M. Cost-optimal reliable power generation in a deep decarbonisation future. *Applied Energy* **253,** 113587 (2019).

65. European Commission. REPowerEU: affordable, secure and sustainable energy for Europe. Available at https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/repowereu-affordable-secure-and-sustainable-energy-europe_en.

66. Strommarkttreffen. Who we are. Available at https://www.strommarkttreffen.org/english/ (2022).

67. van Vuuren, D. P. *et al.* Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm. *Global Environmental Change* **42,** 237–250 (2017).

68. Fricko, O. *et al.* The marker quantification of the Shared Socioeconomic Pathway 2: A middle-of-the-road scenario for the 21st century. *Global Environmental Change* **42,** 251–267 (2017).

69. Fujimori, S. *et al.* SSP3: AIM implementation of Shared Socioeconomic Pathways. *Global Environmental Change* **42,** 268–283 (2017).

70. Calvin, K. *et al.* The SSP4: A world of deepening inequality. *Global Environmental Change* **42,** 284–296 (2017).

71. Kriegler, E. *et al.* Fossil-fueled development (SSP5): An energy and resource intensive scenario for the 21st century. *Global Environmental Change* **42,** 297–315 (2017).