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Energy Systems Integration and Innovation for a Clean Energy Transition

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By

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Committee in charge:

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Abstract

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Noah Reece Kittner

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This dissertation presents a set of analytical tools developed to investigate the energy system transition using a systems approach. The cases explored range from Kosovo, a country on the verge of new electricity supply investments, and future energy pathways to an analytical investigation of innovation in battery storage systems that could unlock the environmental and health benefits of intermittent renewable energy sources such as solar and wind technologies. The analytical tools compare existing metrics such as levelized cost of electricity with new metrics such as a two-factor learning curve of deployment and innovation and trace metal content of coal per final kWh of electricity delivered and energy return on investment of distributed energy systems.

Chapter 1 investigates the case of Kosovo and introduces an analytic framework to analyze electricity costs and environmental impacts of future electricity options. The scheduled decommissioning of the Kosovo A coal-fired power plant provides an opportunity to investigate the changing cost of alternative energy options available in Kosovo for new energy infrastructure. I find that a range of investment pathways from international financial institutions and donor groups could meet the same projected electricity demand at a lower cost than building a new 600 MW coal fired power plant. The options include energy efficiency measures, combinations of solar PV, wind, hydropower, biomass, and the introduction of natural gas. The results indicate that financing a new coal plant is the most expensive pathway to meet future electricity demand in Kosovo.

Chapter 2 utilizes the analytic framework developed to estimate the cost of future electricity pathways and uses green chemistry and public health risk assessment to estimate trace metal content of coal and investigate the air-pollution-related-health risks of lignite coal in Kosovo. By utilizing ICP-MS, I sample lignite coal for trace metal content and develop a risk model to assess future health impacts of air pollution from the electricity options explored in Chapter 1. I find significant trace metal content normalized per kWh of final electricity delivered. I estimate that Kosovo could avoid 2300 premature deaths by 2030 when introducing energy efficiency and solar PV backed up by natural gas. The framework highlights that often multi-lateral development banks do not account for all health risks before guaranteeing loans on new electricity projects. The interest in finding sustainable options to balance the load of intermittent

renewable energy options in Kosovo motivates further analysis to understand how battery storage technologies have developed over time in terms of performance and cost.

Chapter 3 examines the dramatically falling cost of battery storage options. I develop a two-factor technological learning curve model that integrates the value of investment in materials innovation and technology deployment over time from an empirical dataset covering battery storage technology. I find and chart a viable path to dispatchable \$1/W solar with \$100/kWh battery storage that enables combinations of solar, wind, and storage to compete directly with fossil fuel-based electricity options. I highlight the co-evolutionary nature of the cost reductions of battery storage technologies and suggest the relative importance of sustained investment and integration of R&D and deployment to develop innovative low-carbon combined solar, storage, and wind systems.

Chapter 4 highlights the changing energy return on investment of energy technologies by investigating a case in Thailand where distributed solar, mini-hydro, and battery storage mini-grids are becoming an attractive investment and serve as core options to meet growing demand for electricity. I compare the net energy return on investment (EROI) of mini-hydropower, solar PV, and battery storage. This study represents a direct application of the opportunities for battery storage technologies to enable cost-competitive mini-grids in Thailand and around the world.

The dissertation highlights different plans, designs, and future management of cost-effective, sustainable, and healthy electricity systems for a clean energy transition worldwide. The analytical tools presented combine to integrate traditional economic, environmental, and health metrics into energy systems planning and innovation. By integrating these interconnected systems, it becomes possible to enable cleaner and more sustainable energy transitions.

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Additionally, I have greatly benefited from collaborators and mentorship advice from around the world including Sopitsuda Tongsopit, Prof. Shabbir H. Gheewala, Pamela Jagger, Richard Kamens, Savitri Garivait, Garret Tankosic-Kelly, Visar Azemi, Ana Rankovic, Kensuke Yamaguchi, and Felix Lill.

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I have also had the opportunity to mentor a number of undergraduate students who have also helped me grow as a researcher including Joyce Lin, Felicia Lee, Nicole Huang, and Raj Fadadu.

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Preface

This dissertation combines four main chapters that have been published in academic peer-reviewed journals. I have greatly benefitted from forming collaborations and learning from all the parties mentioned. These articles benefit greatly from the collaborators listed. I was the lead author in each study, conceiving and developing the studies as the main contributor. The bibliographic details of each article are listed here:

Kittner, N., Dimco, H., Azemi, V., Tairyan, E., Kammen, D.M. (2016). An analytic framework to assess future electricity options in Kosovo. *Environmental Research Letters*, 11(10), 104013.

Kittner, N., Fadadu, R. P., Buckley, H.L., Schwarzman, M.R., Kammen, D.M. (2018). Trace Metal Content of Coal Exacerbates Air-Pollution-Related Health Risks: The Case of Lignite Coal in Kosovo. *Environmental Science & Technology*, 52, 2359-2367.

Kittner, N., Lill, F., Kammen, D.M. (2017). Energy storage deployment and innovation for the clean energy transition. *Nature Energy*, 2(9), 17125.

Kittner, N., Gheewala, S.H., Kammen, D.M. (2016). Energy return on investment (EROI) of mini-hydro and solar PV systems designed for a mini-grid. *Renewable Energy*, 99, 410-419.

Chapter 1: An analytic framework to assess future electricity options in Kosovo

Abstract:

We have developed an analytic platform to analyze the electricity options, costs, and impacts for Kosovo, a nation that is a critical part of the debate over centralized versus distributed electricity generation and the role of fossil fuels versus cleaner electricity options to meet growing demands for power. We find that a range of alternatives exists to meet present supply constraints all at a lower cost than constructing a proposed 600 MW coal plant. The options include energy efficiency measures, combinations of solar PV, wind, hydropower, and biomass, and the introduction of natural gas. A 30 EUR/ton shadow price on CO_2 increases costs of coal generation by at least 330 million EUR. The results indicate that financing a new coal plant is the most expensive pathway to meet future electricity demand.

1. Introduction

Kosovo is a critical test case for the future financing of new coal-fired power plants by the World Bank, U.S. government, and international financial institutions. The scheduled decommissioning of the Kosovo A coal-fired power plant in 2017 prompted the international lending and donor community to consider providing a loan guarantee for a new coal-fired power plant to replace expected future missing electricity supply (World Bank, 2011). This prompted a systematic analysis of the options that exist to meet electric generation needs compared with a proposed coal-fired power plant. Our analysis examines a suite of alternatives and provides an operational and financial basis for comparison with the coal-intensive proposals. Presenting a unique combination of rising electricity costs, a lack of network connectivity, and the declining cost of renewable technologies over the past five years, Kosovo could be one of several test cases for a country where distributed renewable electricity options become more financially favorable than traditional centralized electricity sector developments (Shirley and Kammen, 2015; Molyneaux et al., 2016).

In 2013, the World Bank issued a policy underscoring its commitment to cease financing new coal projects unless no financially feasible alternatives exist (World Bank, 2013). Because Kosovo represents a case where new preliminary assessments suggested that financially feasible alternatives may exist (Kammen, Mozafari, and Prull, 2012), the decision by the World Bank to finance a new plant in Kosovo could set a precedent for future projects that will test the pledge to cease development lending for new coal-fired power plants in other countries. Since the initial plans for a coal-based future energy scenario for Kosovo were announced, the US Department of the Treasury has also announced an end for U.S. support of public financing for new overseas coal projects with the exception of "very limited circumstances" as part of President Obama's Climate Action Plan (CAP) (US Department of the Treasury, 2013). Additionally, the European Bank for Reconstruction and Development (EBRD) policy requires that the infrastructure being financed is the least carbon-intensive of the realistically available options, keeping in line with other multi-lateral development banks (EBRD, 2013). Future coal-fired generation in a proposed 600 MW coal plant will undermine the pledges by the US Department of Treasury and the World Bank without fully studying alternatives to meet Kosovar power generation challenges.

The analytic framework presented here could be employed by the World Bank or similar international financial institutions (IFIs) to identify whether to fund conventional power sources compared to alternatives on a first approximation. The World Bank already considers safeguard policies in their Environmental and Social Framework for investment project financing. However, our approach provides a quick and low-budget first-cut analysis for comparison of technical and financial feasibility and cost-effectiveness of alternatives. Cost-effectiveness is determined by the World Bank to include "capital and operational cost and financial benefits of the options considered over the life of the project," which this framework includes (World Bank, 2016). Furthermore, it provides a framework that can readily be adapted to include external costs including CO_2 and air pollution impacts of projects. The framework can be applied across a number of large-scale power investment projects, where scenario analysis can be used to identify the presence of alternative options, and then provide opportunities to investigate different pathways in further detail to explore feasibility of low-carbon, low-cost energy sector investments and loan guarantees.

2. The Energy Supply and Demand Picture for Kosovo

Kosovo's power sector currently is not meeting the needs of its population due to frequent blackouts and electricity supply shortages that have required the import of electricity from neighboring countries to serve demand. More than 95% of electric power generation comes from lignite coal in Kosovo. Historically, Kosovo resorted to importing electricity to meet electricity demand needs, therefore placing emphasis on ensuring energy supply security in the future. The political realities of trading electricity supply place Kosovo in a tenuous position, given that a majority of the imports come from Serbia (54% of total electricity imports in 2014 came from Serbia). Serbia does not recognize Kosovo as a sovereign state, and yet exerts significant influence on governance, electricity sales, and water from Gazivoda Lake for cooling Kosovo B (Obradovic-Wochnik & Dodds, 2015). From 2000-2014, there has been a consistently large mismatch between electricity generation and demand. Then in 2014, electricity generation decreased even further, by 17%, from 5,862 GWh to 4,894 GWh, and required an increase in electricity imports to compensate for the artificially capped demand based on physical transmission interconnection and generation constraints (ERO, 2014). Serbia will likely remain one of the key trade partners for electricity in the future due to existing physical transmission infrastructure, underscoring the need to address energy independence and political sensitivities.

This dependence on lignite places it among the highest rates of CO_2 emissions per Euro GDP, with estimates at twice the average level for EU countries, despite a low rate of total CO_2 emissions per capita (MESP, 2014). The UNDP estimated 0.84 tons CO_2/EUR GDP in Kosovo compared to 0.4 tons CO_2/EUR GDP for the rest of the EU (Kabashi et al., 2011; UNDP, 2013). In addition to CO_2 emissions, households in Kosovo also seasonally burn lignite and wood in homes, unfiltered, causing concern for particulate matter and other household air pollution. The UN FAO estimated households consumed an average volume of 8.2 m^3 of wood fuels in rural homes (English et al., 2015). A survey commissioned by the Energy Community estimated about 2,745 GWh of equivalent household heating demand met almost exclusively through biomass consumption (Energy Community, 2012). Further, the use of biomass fuels for household heating means there is a large unmet demand for electricity and looming concerns over household air pollution.

3. State of Renewables in Kosovo

The Kosovar government plans to generate 25% of its energy from renewable sources by 2020. To support this target, feed-in tariffs have emerged over the past two years as a policy support mechanism. As of May 2016, the Energy Regulatory Office fixed solar and wind feed-in tariffs for 12-year terms at 85 €/MWh. Small-hydro feed-in tariffs (<10 MW systems) remain fixed at 10-year terms at 67.47 €/MWh (ERO, 2016). The feed-in tariff levels and targets are summarized in Table 1.

Table 1. Renewable energy 2020 capacity targets and feed-in tariff levels by technology (ERO, 2016).

Renewable Energy Source (RES)	Capacity in 2014 (MW)	2020 Capacity Target (MW)	Feed-in tariff application limits (MW)	Level of feed-in tariff, 12 yrs unless otherwise stated (€/MWh)
Solar PV	3	10	3	85
Solid biomass	2	14	14	71.3
Wind	31.35	150	35	85
New small-hydro power plants (10 yrs)	60	240	10	67.47
Total RES	**96.35**	**414**	**62**	-

Although feed-in tariffs are not the only policy option to support renewable electricity in Kosovo, they have emerged as the main policy driver for renewable development to date. Alternative policies include utility procurement of renewables using avoided cost of generation like in the US, competitive bidding, and the allowance of renewable generators to compete in the wholesale market (Cory et al., 2009; Tongsopit, 2015).

Given the prevalence of fossil-fuel based lignite coal in Kosovo's electricity mix, many observers have posed the question of whether it is realistic to expect that renewables can increase capacity in the next few years. A 2013 GIZ study found that there is at least 290 MW of confirmed wind capacity spread across at least seven sites in Kosovo (GIZ, 2013). Furthermore, a 2014 study by Economic Consulting Associates and Energy Institute Hrvoje Pozar has cited 246 MW of wind planned for 2020 (KOSTT, 2014). In 2015, the first commercial solar producer contracted for power generation in Gjurgjevik with a nameplate capacity of 102 kW and plans to expand to 400 kW (Solar Novus, 2015). Due to technology and policy incentive landscapes, renewable-based electricity has been slow to start, but likely to grow in Kosovo. Small-hydro power plants could fill in generation due to the large technical potential along rivers in the country. Finally, the law in Kosovo requires the purchase of domestic production before seeking trading opportunities, which is a boon for any domestic electricity generation source, including renewable and fossil electricity, though it may reduce the allowance of low-cost electricity imports.

An External Expert Panel to the World Bank estimated the LCOE of a new coal power plant in Kosovo at approximately €81.42/MWh (Beer et al., 2012). By the time of completion this cost level will be uncompetitive with renewable generation and the price that electricity is traded within neighboring power exchanges, as electricity traded in the Coordinated Auction Office in Southeast Europe (SEE CAO) hovered between €10-60/MWh during 2013 and 2014

(SEE CAO, 2015). Figure 2 highlights the base market spot prices for electricity traded in the South East Europe market, which represents a realistic option since Kosovo is part of the Energy Community, a shareholder in SEE CAO, and a part of the ENSTO-E system. If electricity in Hungary is traded at €40-45/MWh, it will pressure Kosovar producers to stay at this price level to remain competitive with neighboring power markets. An open regional market could allow for imports of electricity at significantly less than the LCOE of coal based on historical prices in 2013 and 2014. These prices remain consistent with the Hungarian Power Exchange, which maintained base and peak average prices of €40.5/40.6-€47.02-46.84 EUR/MWh in 2014 and 2015 respectively and crosses fewer borders than the nearby Energy Exchange Austria (HUPX, 2015).

Kosovo is considered a potential candidate to join the EU and already signatory on the EU Energy Treaty (European Commission, 2016). Though the drive and ability for Kosovo to join the EU does not directly hinge on the electricity system, meeting climate and energy targets set by the EU could expedite the process (Kammen and Kittner, 2015; Kittner et al., 2016). Kosovo will likely move into an emerging open regional power market, where it would become part of the European integrated energy market. KOSTT is already a shareholder in the Coordinated Auction Office for South East Europe and a part of the Energy Community Treaty, furthering the rationale for moving toward a single market for energy within the EU (Prange-Gstohl, 2009). The responsibility of trading now falls with the distributor, KEDS. Therefore, daily, monthly, emergency, and spot pricing will impact the import price for Kosovo. The existing and planned grid interconnections position Kosovo to become a regional power market player. Significant opportunities exist in the region for electricity trading due to differences in resource portfolios and the potential for inter-temporal substitution of electricity from various sources (Hooper and Medvedev, 2009).

4. Data

There has been little empirical work studying the power sector in Kosovo and the South East Europe region, despite increasing urgency to decarbonize South East Europe's power sector (Dominkovic et al., 2016; Kittner et al., 2016). Few studies have undertaken detailed systems-scale energy transition analyses due to regional conflict, though KfW and national entities have begun to engage with higher resolution resource assessments (Kammen et al., 2012; Bjelic and Ciric, 2014). Because the power sector faces pressing informational needs due to rising forecasted demand, power generation challenges, and future regional grid integration, providing reliable and secure electricity remains a critical development challenge. The data for this study represent the best available information given the limitations of resource availability assessments in the region, yet provide useful information that can inform electricity capacity planning efforts. The decreased capital cost of key renewable technologies including solar PV and wind within South East Europe provides insights into the cost of developing renewable energy in Kosovo (IRENA, 2015). The European Commission has enacted stricter greenhouse gas emission reduction targets along with increased energy efficiency, renewable generation goals, and plans for expanding regional interconnections. Joining the EU – a goal expressed publicly by all Kosovar leaders -- would be a major driver of change in the energy mix to meet the standards imposed by the Industrial Emissions Directive. Additionally, Kosovo would need to follow the 2030 climate and energy framework, which stipulate a 40% reduction in greenhouse gas emissions from 1990 levels, raising the share of renewable energy generation to 27%, and a 27% improvement in energy efficiency (EU, 2015a; EU, 2015b).

The cost data for this study comes from the latest estimates in South East Europe for the levelized cost of energy by leading market research firms and expert elicitation validated by regional governments, private industry, and 17 civil society organizations (Fraunhofer, 2013; Kittner et al., 2016). The global reductions over the past five years in the LCOE of renewables open the door for a wide variety of alternative scenarios to investigate further. The cost of generation in our analysis captures capital investment costs, fixed and variable operation and maintenance (O&M) costs, and also the cost of fuel (for coal and natural gas) in Table 2. The construction times presented for distributed renewables are based on stakeholder consultation with industry and civil society based in South East Europe. We assume that they are reasonable and should be viewed relative to one another, as solar PV projects are often quicker to construct and deploy than mini-hydropower or wind projects (Kittner et al., 2016). Small-scale hydropower and wind projects are often quicker to construct and deploy than large scale coal power plants or natural gas combustion turbines.

Table 2. Lower and upper bound capital investment costs for new generation capacity in 2016 in Kosovo.

	2016 Capital Costs [EUR/kW]						
Technology	**Investment Low Price**	**Investment High Price**	**Variable OM Costs [EUR/kWh]**	**Fixed OM Costs [EUR/kW-yr]**	**Lifetime [years]**	**Capacity factor**	**Construction time [years]**
Brown lignite	1600	2300	0.1	17	40	85%	3
Hydropower run-of-river	1300	3300	-	85	50	55%	2
Wind onshore	1100	1340	-	31	25	25%	2
Solar PV residential	1100	1300	-	8	30	18%	1
Solar PV commercial	1000	1200	-	7	30	18%	1
Solar PV utility scale	1000	1100	-	7	30	18%	1
Biomass (steam turbine)	2300	4400	0.4	15	30	25%	2
Waste-to-energy (steam turbine)	4000	4400	0.1	20	25	75%	2
Conventional natural gas combined cycle	670	1200	0.1	20	25	75%	3

5. Methods

We created an annual generation spreadsheet model to estimate electricity generation and the cost of supplying electricity using different technologies. The model is based on an accounting stock of existing infrastructure in Kosovo and explores the cost of meeting energy supply needs through different pathways. This is not an hourly model. Neither does it model to the resolution of capacity expansion models like SWITCH because this model provides a scenario-based framework to address uncertainty under low-data availability (Nelson et al., 2012; Ponce de Leon Barido et al., 2015; He et al., 2016). The model backcasts annual generation and costs based on different policy parameters detailed in each scenario. Each scenario contains a target capacity of solar, wind, and biomass resources. The model estimates the potential generation based on available resources and policy targets. Also, the spreadsheet calculates life cycle costs of the projects to also estimate the levelized cost of electricity. The spreadsheet first estimates annual generation from each scenario and sums the annual generation across electricity supply technologies. Then the costs of each scenario across the life of the project are calculated using capital investment, fixed and variable O&M, and fuel price estimates to represent the cost of building each scenario in the South East European context. A table of capital investment prices for different generation technologies is used as input parameters for the cost. The costs are then amortized over the life of the project into net present value. The net present value estimations for the different scenarios are used for comparing the scenarios against each other on a cost basis. The spreadsheet does not pick the least cost option; it provides opportunities to examine different pathways of electricity generation.

We apply a 3.2% linear growth rate to forecast electricity demand based on a previous analysis using HOMER, which remains consistent with projected increases in per capita electricity consumption (Kammen et al, 2012). We assume that each hour in one day has the same peak demand for an entire month, due to the available load shape data as a monthly average, which includes seasonal variation due to increased wintertime electricity demand.

We incorporate previous analyses and parameters of Kosovo's power sector that optimized electricity generation using HOMER (Kammen et al, 2012). Then we developed realistic scenarios based on varying technology and policy choices that provide a framework to investigate the cost and generation of Kosovo's power sector. The data are from the latest levelized cost of energy projections determined by Fraunhofer and UK DECC 2050 South East Europe Carbon Calculator, representing prices within South East Europe. Investment and capital costs are included in this calculation, as the LCOE comprises total capital cost, fixed and variable O&M, fuel price, and construction time.

$$LCOE = \frac{\{capital\ investment\ cost * capital\ recovery\ factor + fixed\ O\&M)}{8760 * capacity\ factor} + (fuel\ cost * heatrate) + variable\ O\&M$$

We base capacity factors for different technologies on previous reports that estimate resource availability for renewable technologies and historical generation from existing power plants using information from KOSTT. We simulate electricity generation for each technology type and the cost to build each scenario using capital fixed costs, operating costs, and amortize until 2025. We do not model ramping constraints. Electricity imports fill the missing generation to satisfy demand. Distributed generation and intermittent renewable electricity have substantial implications for grid operation. The model presented here deals with these implications as added costs to individual technologies, which may be optimistic since it does not incorporate real power flow. Each scenario represents a different alternative pathway that highlights the numerous opportunities for development in the region. The base case presents a business as usual approach if the World Bank approves financing for Kosovo C. Additionally we estimate the cost difference from the base scenario when introducing a €30/ton shadow price of CO_2 when using coal. Lignite coal is one of the lowest quality types of coal and could release 5.8 million tons of CO_2/year in Kosovo's electricity sector (Kammen et al., 2012). In multiple scenarios, Kosovo A must close down by 2017, as it will approach its end-of-life unless we apply retrofit investments to follow the "best available techniques" outlined in accordance with the Industrial Emissions Directive. The base case scenario continues operation of Kosovo B beyond 2025. Details of the scenarios are found in the supplementary materials.

6. Results

The results indicate a wide range of options that meet electricity generation requirements at a lower cost than the base case. Table 3 summarizes the scenarios. The Energy Strategy for Kosovo established specific goals for capacity expansion for renewables.

Table 3. A selection of the multiple pathways examined in this paper that economically and reliably meet Kosovo's projected future electricity demand.

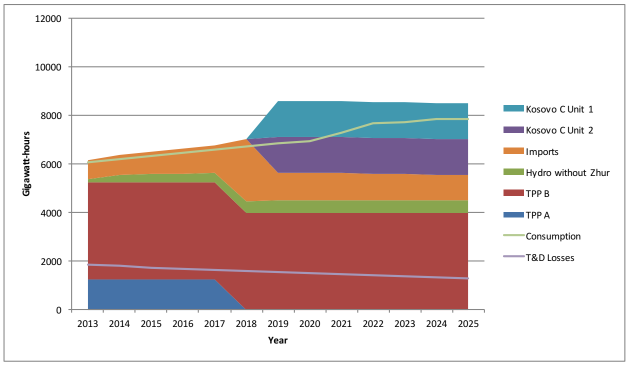
Scenario	**Name**	**Notes**
1	**Base Case (coal)**	TPP C built in 2017, 2-300 MW turbines
2	Solar Prices Reduce to SunShot Levels	Solar at €0.9/W by 2020; €30/ton of CO_2
3	Euro 2030 path: Aggressive energy efficiency measures (27% increase), 27% CO_2 reduction, 27% renewable consumption along with expanded open regional market via a power exchange	1 kWh energy avoided displaces 1 kWh coal-fired generation
4	Regional transmission network allows for expanded electricity imports	Solar at €1/W by 2020 and imports dominate from Hungarian Power exchange
5	Introduction of natural gas via TAP by 2018 with aggressive energy efficiency measures	Solar at €1/W by 2020
6	Including a carbon shadow price	€30/ton of CO_2 added to cost of coal generation
7	Including storage cost for solar at high deployment levels No natural gas, extra transmission for Albania-Kosovar joint projects	Solar at €1/W by 2020 and storage is €200/kWh

We estimated the cost of different renewable energy technologies and the amount of electricity generated based on different capacities for each technology. Each scenario and cost estimate is summarized in Table 4.

The cost assumptions influenced the capacity deployed of each technology in different years. Using resource availability data, we estimated annual generation from each type of electricity and the associated cost, annualized over a twelve-year period. The base case scenario, Figure 1.1, assumes Kosovo C is built in 2017 and 98% of Kosovo's electricity generation comes from brown lignite coal. Figure 1.2 highlights the scenario where solar prices reduce to SunShot levels of €0.9/W by 2020, TPP A ceases production before 2018, there is a €30/ton price on CO_2, and we assume a 3% yearly improvement in transmission and distribution losses. Albanian-Kosovar joint projects and small hydropower reserves balance the system and provide flexibility to accommodate intermittent solar as a part of an open regional market. We added a storage penalty to account for the intermittency of solar PV, by appending 10% of system costs per kWh to each kWh of solar generated in Figure 1.5 (Gur et al., 2012).

The estimated grid consumption data comes from projections by the Ministry of Economic Development along with expected population growth. Figure 1.2 exhibits the increased ability of solar PV to meet electricity needs, ramping up in magnitude starting in 2020 if the price of solar reduces to €0.9/W, a current policy goal of the US government under the SunShot pricing program, adapted to South East Europe. These prices are reasonable because of the global competitiveness of the solar PV market and remain consistent with projections for the cost of solar PV in southeast Europe. An aggressive energy efficiency scenario, detailed in Figure 1.3, exhibits the potential to curtail growth in peak energy consumption to 5000-7000 GWh and meeting EU 2030 energy efficiency targets. Figure 1.4 introduces low-cost energy imports from an open regional market, which allows solar to develop along with available hydropower resources. Figure 1.5 introduces natural gas to Kosovo's electricity portfolio by 2018 and gas quickly facilitates a rise in solar PV deployment due to the ability to serve as a fast-ramping, flexible generator that compensates for the variability of solar PV due to cloudiness. Given that bringing TAP or IAP is an official policy of the Government of Kosovo, a scenario incorporating natural gas should be analyzed. With the introduction of gas, the demand for coal generation disappears by 2022. The results highlight the wide variety of options Kosovo has to meet its future electricity demand at lower cost than building Kosovo C and the opportunities for Kosovo to become an energy hub by exporting electricity to neighboring states.

In Figure 1.6, we test the sensitivity by including a shadow price of €30/ton of CO_2 without aggressive cost reductions for solar, as World Bank President Jim Kim has suggested should be accounted for when planning new World Bank projects. We estimate that the construction of Kosovo C could add up to 11.5 million tons of CO_2 per year, adding an additional amortized cost of €330 million for the plant.



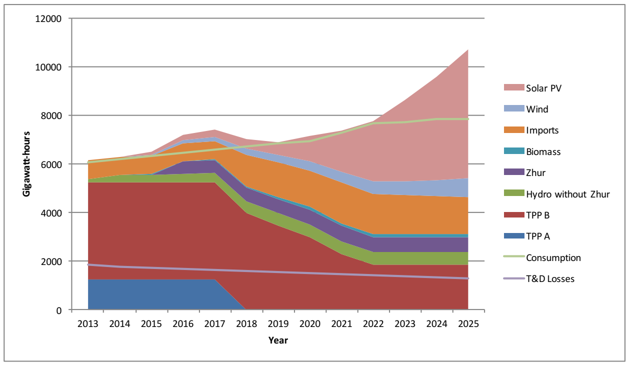
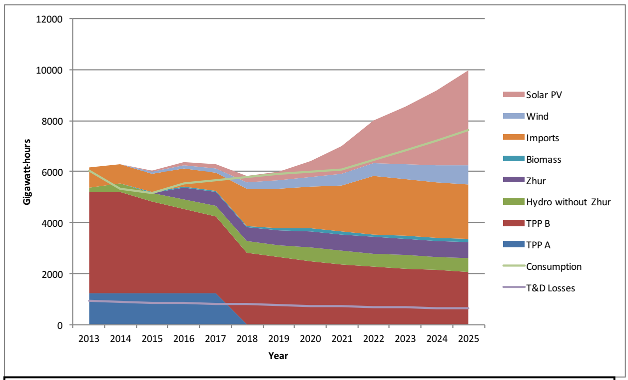


Figure 1.1. Base Case (Kosovo C built in 2017)

Figure 1.2. Solar reaches SunShot Prices (€0.9/W) by 2020.



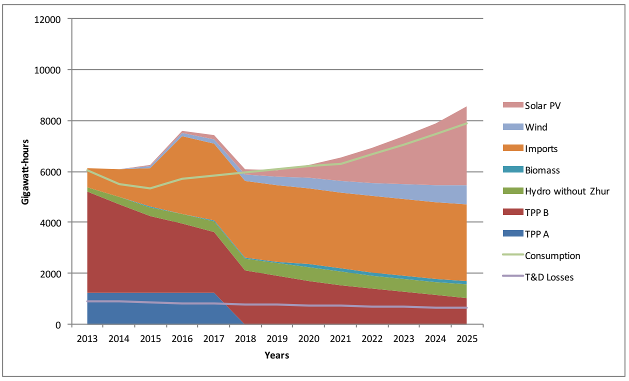
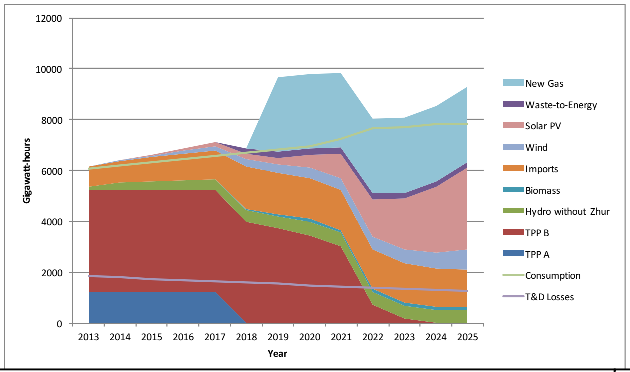


Figure 1.3. Euro 2030 path: Energy efficiency measures (27% increase), 27% CO_2 reduction, >27% renewable consumption, expanded power exchange.

Figure 1.4. Regional transmission network allows for expanded electricity imports



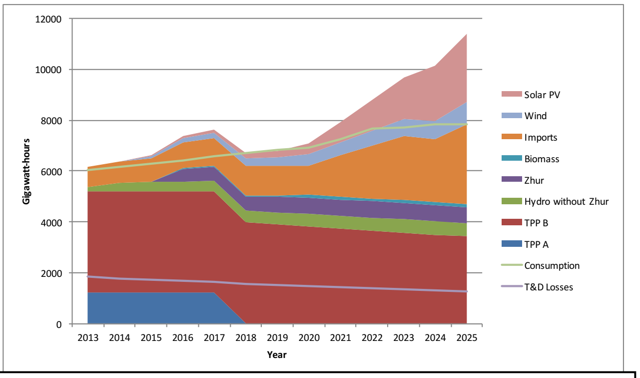


Figure 1.5. Introduction of natural gas via TAP by 2018 with aggressive energy efficiency measures.

Figure 1.6. Carbon Shadow Price of €30/ton CO_2

Scenario	**Name**	**Notes**	**Estimated Cost**[*]	**Average LCOE**	**Figure**
1	**Base Case (coal)**	"New Kosovo" built in 2017; 2-300 MW turbines	**€1.96 billion EUR (€2.29 billion EUR with €30/ton CO_2 price, €1.86 billion EUR at 500 MW)**	€204/MWh (€184/MWh-€224/MWh)	Figure 1.1
2	Solar Prices Reduce to SunShot Levels	Solar at €0.9/W by 2020; €30/ton of CO_2	€1.67 billion EUR	€165/MWh (€156/MWh-€174/MWh)	Figure 1.2
3	Euro 2030 path: Aggressive energy efficiency measures (27% increase), 27% CO_2 reduction, 27% renewable consumption along with expanded open regional market via a power exchange	1 kWh energy avoided displaces 1 kWh coal-fired generation	€1.57 billion EUR	€160/MWh (€150/MWh-€170/MWh)	Figure 1.3; Appendix Table A.3
4	Regional transmission network allows for expanded electricity imports	Solar at €1/W by 2020 and imports dominate from Hungarian Power exchange	€1.76 billion EUR	€167/MWh (€162/MWh-€172/MWh)	Figure 1.4; Appendix Table A.4
5	Introduction of natural gas via TAP by 2018 with aggressive energy efficiency measures	Solar at €1/W by 2020	€1.55 billion EUR	€155/MWh (€141/MWh-€169/MWh)	Figure 1.5; Appendix Table A.5

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[*] See Supplemental Materials for detailed annualized cost estimation. We use currency exchange of 1.1 USD = 1 EUR based on 2016 rates.

6	Including a carbon shadow price	€30/ton of CO_2 added to cost of coal generation	€1.78 billion EUR	€169/MWh (€160/MWh-€178/MWh)	Figure 1.6; Appendix Table A.6
7	Including storage cost for solar at high deployment levels	Solar at €1/W by 2020 and storage penalty at €200/kWh, representing 10% of system generation costs	€1.57 billion EUR	€157/MWh (€150/MWh-€164/MWh)	Not pictured; Appendix Table A.7

Table 4. Total cost estimates of each scenario including business-as-usual case. Technology costs are based on current operating costs (BAU), and renewable energy technology costs as estimated by the Global Energy Assessment (2012) project, Fraunhofer (2013), Bloomberg New Energy Finance (2016), and regional stakeholder consultations (Kittner et al., 2016).

Each of the different non-Kosovo C scenarios will provide electricity until at least 2025 at a cost of less than €1.5-1.8 billion euros. This is significantly less than an estimated cost of €1.9-2.2 billion euros to follow a coal-based trajectory. Ongoing international discussions around the Kosovo C option have focused on installing two 300 MW coal-fired subcritical boilers (~ 37% thermal efficiency) which indicates that a) the cleanest conventional coal plants are not being considered, largely due to cost concerns, and b) the human and environmental health impacts of the baseline coal project will be significantly higher than the most recent epidemiological studies on higher ranking bituminous and anthracite coal (Epstein et al., 2011; Treyer et al., 2014). Selection of these less societally damaging coal options, which international World Bank policies designed to minimize harms on people and the environment would warrant, increase the price gap between the clean energy cases and the coal scenario further when adding external costs to the analysis. The alternative pathways presented could save the Kosovo Energy Distribution and Supply Company (KEDS) between €200-400 million euros before considering health, job creation, or societal benefits of a more resilient system. This upper-bound estimate does not include any externalities. If we apply a shadow price of €30/ton of CO_2, the difference between each scenario and the base case could double. This is based on estimated costs of capacity expansion only and does not model AC power flow across the grid. We caveat the results that the costs are based on expanding generation capacity.

7. Discussion

Particularly important in this work is the observation that there are multiple, economically realistic scenarios that can provide reliable, low-carbon electricity for Kosovo. Technical and political preferences may lead different analysts to prefer different energy mixtures, but the diversity of viable cases leads to three clear conclusions:

- There is no shortage of low-cost, low-carbon paths that Kosovo and international investment and development partners could follow;

- As a result of the above, a coal-dominated future is neither an economic nor political necessity. In ongoing work, the job creation and both human and environmental health benefits of these non-coal scenarios will be further detailed, which makes the case for a multi-billion dollar coal-based pathway unnecessary.
- A diversity of low-carbon pathways requires further discussion and action; the range of options presented, in fact, may make the pathway to a decision challenging in a contentious environment.

Due to capital constraints within the region, the €200-400 million EUR difference in costs per scenario is not trivial. The health costs of lignite in terms of particulate and sulfur emissions would increase the gap between options that reduce coal generation even further (Ukehaxhaj et al, 2013; World Bank, 2013; Holland, 2016).

The capacity for distributed renewables can be increased as needed compared to large centralized projects. For instance, developers can install solar PV incrementally on a per kW or MW scale, whereas a coal plant requires full commitment to hundreds of MW capacity during one investment period. As demand for electricity changes, the deployment of distributed renewables provides investors with increased flexibility to extend capacity in smaller sizes as to not leave the investor with large-scale stranded assets. This also increases domestic electricity production which could become advantageous for Kosovo in a future regional power market.

8. Policy implications

Energy security has emerged as an important policy goal within South East European countries. The different pathways presented in this paper fall within different energy security policy packages including expanding generation capacity within Kosovo and access to electricity and simultaneously responding to looming threats of global climate change. Coal specifically poses certain security challenges including the tradeoff of being plentiful, yet finite in supply. The resource curse of coal could constrain Kosovo's future economic development, as diversity and availability of resources remain key components of any national energy security plan (Sovacool & Brown, 2010; Sovacool & Saunders, 2014; Tongsopit et al., 2016). The alternative pathways detailed in this analysis highlight the range of domestic renewable resources that would reduce government debt and improve energy security. A focus on managing risk through diversification of resources, where Kosovo currently relies on 98% lignite could reduce the recent price surges consumers have faced due to unreliable generation capacity from Kosovo A and Kosovo B. Decentralized and domestic run-of-river hydropower, solar electricity, and biomass resources open up opportunities for regional power trading. An open market could enable Kosovo to become an energy producer of surplus electricity and sell to neighboring countries, since nearly all countries in the region (Albania, Bulgaria, Serbia, and Macedonia) suffer from energy supply shortages on a frequent basis. This would improve the situation from the current reliance on imports from Serbia by facilitating future mutual electricity exchanges that could benefit grid integration, operations, electricity costs, and the environment.

The ripple effects of decisions on Kosovo's power sector will hold a large influence over the future debates to construct new coal-fired power plants in sub-Saharan Africa, India, and Pakistan by setting a precedent for multi-lateral lending institutions. The lending policy opens the conversation for how constrained an economy must be to qualify for the exception in the World Bank's policy, as technically Kosovo resembles a middle-income country (officially classified as IDA/Blend) compared to other countries that may lack significantly more economic resources.

9. Conclusions

As demonstrated through the range of alternative energy pathways, the opportunity cost of building a new coal-fired power plant is high. The policy implications of the proposed coal plant are pervasive throughout the economics of coal, multi-lateral development bank finance policy, and energy security as a national development strategy. The scenario results provide a framework to evaluate policy risk from multiple stakeholders, including the Government of Kosovo, the World Bank, and the US Government as a direct benefactor of energy lending to multi-lateral development banks.

We find that a range of technically and economically viable clean electricity paths exists to meet Kosovo's near and long-term electricity needs based on the analytic framework. The scenarios that emphasize a variety of renewable electricity resources – notably solar, wind, and hydropower, in concert with judicious use of fossil fuels that are employed with a clear end game of a decarbonized and reliable electricity grid – afford Kosovo with an array of advantages. Significant in the cases examined is the consistently estimated lower overall net present cost relative to the business-as-usual coal-based pathway. In addition, each scenario emphasizing renewable energy provides more energy than the forecast demand, opening the door for regional power trading and exports, which have significant capacity to build security, regional prosperity, and peace, as well as bringing Kosovo's carbon emissions closer to the EU standard. This report highlights that Kosovo's energy future will not depend on the economy or technology, yet will remain a policy choice with significant implications for the electricity sector, public health, and the environment.

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Supplemental Material

1. Study area

This study models the cost of building new generation capacity within the power sector in Kosovo. We locate all generation and construction projects within Kosovo and we also investigate the opportunities to participate in an open regional market via a power-trading scheme that would include Albanian-Kosovar joint projects and imported electricity from Romania. The World Bank designates Kosovo as a Lower Middle Income country with a GDP in 2015 of approximately $6.39 billion USD (5.75 billion EUR) and a population of 1.797 million (World Bank, 2016). The country spans an area of approximately 10,908 square kilometers within the Balkan region.

Scenario	Description
Base Case	New coal generation 2-300 MW turbines online to replace Kosovo A (1-500 MW turbine in alternate scenario) 140 MW small hydro Imports fill remaining generation
SunShot Solar - Aggressive	No new coal Kosovo A closes in 2017 Kosovo B remains operational 650 MW solar by 2020 140 MW small hydro 450 MW wind by 2025 165 MW biomass by 2020 170 MW large hydro
Euro 2030 Path	No new coal Kosovo A closes in 2017 Kosovo B remains operationa 20% improvement in energy efficiency by 2020 1 kWh coal displaced in generation for every kWh of efficiency improvement from base case 20% renewable energy target by 2020 292.5 MW solar by 2020 140 MW small hydro 450 MW wind by 2025 165 MW biomass by 2020 Imports to meet extra generation demand
No natural gas, extra transmission for Albania-Kosovar joint projects	140 MW small hydro 450 MW wind by 2025 165 MW biomass by 2020 Imports to meet extra generation demand

Introduction of natural gas	140 MW small hydro 405 MW solar by 2020 450 MW wind by 2025 500 MW gas via TAP 165 MW biomass
Carbon Shadow Price	140 MW small hydro 430 MW solar by 2020 450 MW wind by 2025
Storage penalty, natural gas, not pictured	140 MW small hydro 405 MW solar by 2020 450 MW wind by 2025 500 MW gas via TAP

	2016 Capital Costs [EUR/kW]						
Technology	**Investment Low Price**	**Investment High Price**	**Variable OM Costs [EUR/kWh]**	**Fixed OM Costs [EUR/kW-yr]**	**Lifetime [years]**	**Capacity factor**	**Construction time [years]**
Brown lignite	1600	2300	0.1	17	40	85%	3
Hydropower run-of-river	1300	3300	-	85	50	55%	2
Wind onshore	1100	1340	-	31	25	25%	2
Solar PV residential	1100	1300	-	8	30	18%	1
Solar PV commercial	1000	1200	-	7	30	18%	1
Solar PV utility scale	1000	1100	-	7	30	18%	1
Biomass (steam turbine)	2300	4400	0.4	15	30	25%	2
Waste-to-energy (steam turbine)	4000	4400	0.1	20	25	75%	2
Conventional natural gas combined cycle	670	1200	0.1	20	25	75%	3

$$LCOE = \frac{\{capital\ investment\ cost * capital\ recovery\ factor + fixed\ O\&M)}{8760 * capacity\ factor} + (fuel\ cost * heatrate) + variable\ O\&M$$

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1}$$

Where *i* = discount rate, *n* = period, and *CRF* = capital recovery factor

1.2 Resource Availability

1.2.1 Coal Reserves

There is an estimated potential of 10.9-12.5 billion tonnes of domestic lignite coal reserves. However, despite this available resource, lignite coal has the lowest carbon content, highest amount of moisture, and lowest energy density compared to other types of coal. Significant health and environmental problems arise from its continued use (Treyer et al., 2014). Even the process of converting lignite from mining and extraction into a usable form is more energy intensive than other types of coal production. It's unlikely the proposed power plant, "New Kosovo," would utilize the best available technologies for pollution control and carbon capture and storage due to the proposed subcritical boilers (World Bank, 2011).

			Assumptions	
	Unit	**Year**	**2010**	***2015***
Capex	EUR/kW	Low	1600	1600
	EUR/kW	High	2300	2300
Fuel costs	MEUR/TWh	Low	10.5	*9*
	MEUR/TWh	High	10.5	*11*
Variable O&M	EUR/kWh	Low	0.1	0.1
	EUR/kWh	High	0.1	0.1
Fixed O&M	EUR/kW-yr	Low	13	*17*
	EUR/kW-yr	High	17	*17*
Life time	years	40		-
Construction time	years	3		
WACC	%	7%		
Cost of equity	%	-		
Cost of debt	%	-		
Debt ratio	%	-		
Capacity factor			85%	85%

1.2.2 Solar resource availability

We use regional resource estimates to estimate solar PV generation. The annual incoming solar radiation ranges from 1550 kWh/m^2/year to 1650 kWh/m^2/year at 35° inclination (European Commission, 2008). There is not much regional variation across the country (less than 10%), so we use an average of 1600 kWh/m^2/year to estimate the generation as shown in Figure 1. There is more solar resource available in the southwest toward Prizren, however the differences within the country differ by less than 10%. We include a capacity factor of 18% for solar photovoltaic installations. We assume that the plant operated at 13% efficiency at STC including an AC derating factor of

87%. Hernandez et al. (2014) find in California a land-use efficiency for utility scale installations at 35.0 Wm^{-2}, this would translate to an approximate requirement 30 km^2 maximum to development nearly 3 GW of solar PV capacity in the country. Under these assumption, Kosovo could adequately promote solar with an area of 10,908 km^2, therefore this would only require 0.2% of total land in the country.

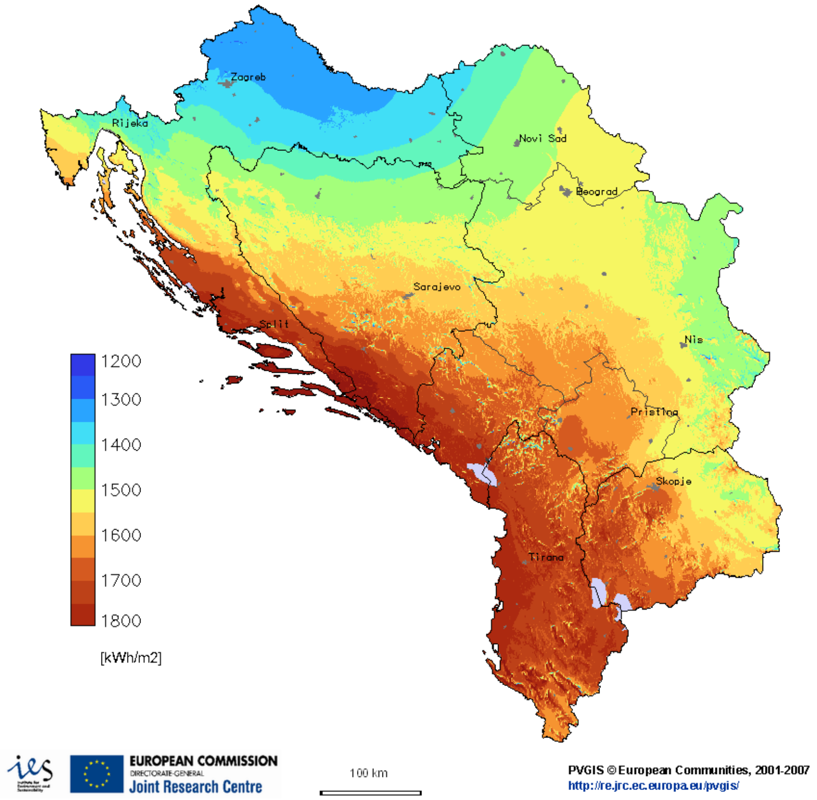

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Figure 1. Solar radiation across Balkan region, with 35 degree inclination, facing south.

	Unit	Year	Assumptions	
			2010	***2015 (est'd)***
Capex	EUR/kW	Low	1,300	1,100
	EUR/kW	High	1,100	1,100
Fuel costs	EUR/kWh	Low		
	EUR/kWh	High		
Variable O&M	EUR/kWh	Low		
	EUR/kWh	High		
Fixed O&M	EUR/kW-yr	Low	7	*7*

	EUR/kW-yr	High	30	*30*
Life time	years		25	*30*
Construction time	years	1		
WACC	%	7%		
Cost of equity	%	-		
Cost of debt	%	-		
Debt ratio	%	-		
Capacity factor			18%	

1.2.3 Hydroelectric power

We separate hydropower into two different classifications. We treat reservoir-based traditional hydropower as large-scale hydropower projects and we investigate run-of-river small-scale mini-hydropower projects.

1.2.3.1 Large-scale hydropower projects

This analysis explores scenarios where a major proposed hydropower project, Zhur is built and when it is not constructed. The proposed location of Zhur is between Prizren and Dragash. The plans for Zhur have been modified as original documentation proposed a 305 MW facility with annual production of approximately 400 GWh. However, we do not model scenarios with a 305 MW facility as we expect Zhur to be approximately 45 MW in capacity if it is built (Ministry of Energy and Industry, *personal communication*). This large-scale hydropower facility would be the only one of its type. As a reservoir-based large-scale hydropower facility, Zhur could provide peaking support to accommodate the variability in the current grid, which is not reliable. This facility would also support the development of intermittent renewables by providing a dispatchable, load-balancing generation source. The hydropower portfolio matches well with coincident demand in Kosovo, which could provide peaking support in the absence of or combined with natural gas (European Commission, 2014). The 45 MW would only have a capacity factor of approximately 15% to provide peaking support and assuming low production due to water availability.

1.2.3.2. Run-of-river hydropower projects

There is an aggregated potential to develop approximately 63 MW of small-scale, run-of-river, mini-hydropower projects across Kosovo due to the presence of many rivers with sufficient resources ranging from 3-21 meters of gross head and greater than 4 cm^3/s of flow based on a feasibility study carried out across Kosovo's water resources (Kammen et al., 2012). This resource could provide nearly 300 GWh of electric generation per year. Even more supportive of hydropower development, the Energy Regulatory Office (ERO) in Kosovo expects 140.3 MW of run-of-river capacity by 2020. The average capacity factor for these resources is estimated at 55%.

			Assumptions	
	Units	**Year**	**2010**	**2015 (est'd)**
Capex	EUR/kW	Low	1,500	1,300
	EUR/kW	High	3,300	3,30
Fuel costs	MEUR/TWh	Low		
	MEUR/TWh	High		
Variable O&M	EUR/kWh	Low		

	EUR/kWh	High		
Fixed O&M	EUR/kW-yr	Low (2.5%)	85	85
	EUR/kW-yr	High (2.5%)	100	100
Life time	years	50		
Construction time	years	2		
WACC	%	7%		
Cost of equity	%	-		
Cost of debt	%	-		
Debt ratio	%	-		
Capacity factor			55%	55%

1.2.4 Wind resource

The estimated average annual wind-speed from Budakova at 38 meters is approximately 6.9 m/s. Figure 4 exhibits the monthly average wind resource. We use the log law to extrapolate wind speed at commercial hub of 90 meters to 7.4 m/s using a roughness class of 1 based on the European Wind Atlas classification. This assumption does not consider scaling changes during the time-of-day or temperature fluctuations that would affect wind speed. We only compute power from the average wind speed, which is a limitation on our analysis. However, the mountainous terrain of Kosovo provides many available sites located near municipalities with potential for wind power generation. Wind projects in the pipeline include the development of 140 MW of wind by NEK Umwelttechnik, a Swiss firm, beginning with the Zatric wind farm project with a capacity of up to 45 MW. The other projects include the Budakove wind farm and Cicavices, which could come online by 2016 (NEK, 2013). It would require a land area of less than 1 km^2 to develop the wind in all scenarios (McDonald et al., 2009).

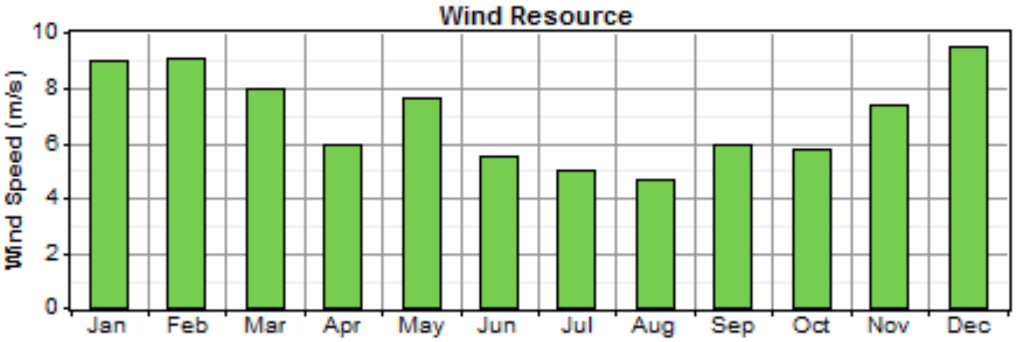

Figure 2. Monthly wind speed (m/s) in Budakova.

	Unit	**Year**	**Assumptions**	
			2010	***2015 (est'd)***
Capex	EUR/kW	Low	1,300	1,100
	EUR/kW	High	1,550	1,340
Fuel costs	EUR/kWh	Low		

	EUR/kWh	High		
Variable O&M	EUR/kWh	Low		
	EUR/kWh	High		
Fixed O&M	EUR/kW-yr	Low	33	31
	EUR/kW-yr	High	39	31
Life time	years	25	25	25
Construction time	years		2	2
WACC	%		7%	7%
Cost of equity	%	-		
Cost of debt	%	-		
Debt ratio	%	-		
Capacity factor			25%	25%

1.2.5. Biomass

The theoretical potential for electricity generation from biomass sources in Kosovo comes from three main types of biomass—wood, livestock waste, and agricultural straw. We estimate approximately 6600 GWh/yr of theoretical annual energy from biomass resources available in Kosovo. Furthermore, a household survey on biomass recently estimated that 1.6 million cubic meters of biomass are harvested annually (Waschak et al., 2013). Even though this represents a 300,000-400,000 cubic meters above the recommended levels of wood harvesting, improved forest management policies and practices could enable a sustainable biomass resource for electricity consumption (NFG, 2012). This would facilitate the development of more promising, lower-cost renewables including solar PV and wind. An important area for further study is the potential in Kosovo to aggregate and utilize biomass as both a dispatchable renewable energy resource, but also potentially as a means to technologically leapfrog and include a net carbon negative energy component. Recent studies in other regions (Sanchez, et al., 2015) open the door for further studies that have additional benefits of strong job creation potential (Wei, Patadia, and Kammen, 2010).

	Unit	**Year**	**Assumptions**	
			2010	***2015 (est'd)***
Capex	EUR/kW	Low	2,300	2,300
	EUR/kW	High	4,400	4,400
Fuel costs	EUR/kWh	Low		
	EUR/kWh	High		
Variable O&M	EUR/kWh	Low		
	EUR/kWh	High		
Fixed O&M	EUR/kW-yr	Low	15	15
	EUR/kW-yr	High	15	15
Life time	years	25	25	25
Construction time	years		2	2
WACC	%		7%	7%
Cost of equity	%	-		

Cost of debt	%	-		
Debt ratio	%	-		
Capacity factor			25%	25%

1.2.6. Waste-to-energy projects

Another resource explored in this study is waste incineration. The Government of Kosovo (GoK) estimates annual urban waste of 192 kg per capita, which represents approximately 384,000 tons/year (GoK, 2012). This study assumes that 1 ton of waste is equivalent to 670 kWh of electricity generation, and 10% of the electricity generated is lost to waste recycling. This type of technology is based on landfill cogeneration and Kosovo has the advantage of using central heating. Incineration or burning of waste by advanced technologies could contribute to a small portion of overall electricity generation.

Year	**Unit**		**Assumptions**	
			2010	**2015 (est'd)**
Capex	EUR/kW	Low	4000	4000
	EUR/kW	High	4400	4400
Fuel costs	MEUR/TWh	Low	27	25
	MEUR/TWh	High	27	30
Variable O&M	EUR/kWh	Low	0.1	
	EUR/kWh	High	0.1	
Fixed O&M	EUR/kW-yr	Low	20	20
	EUR/kW-yr	High	20	20
Life time	years	25		-
Construction time	years	3		
WACC	%	7%		
Cost of equity	%	-		
Cost of debt	%	-		
Debt ratio	%	-		
Capacity factor			89%	75%
Thermal efficiency	%		53%	56%

1.2.7 Energy efficiency measures

Energy efficiency is a critical resource for planning Kosovo's future electric grid. Currently, Kosovo represents a "non energy-efficient" country, however, this sector must improve to meet European Union integration requirements. The World Bank already approved a $31 million USD loan to establish the Kosovo Energy Efficiency and Renewable Energy Project.

Transmission and distribution inefficiencies along the grid account for significant technical energy losses. Approximately 33% of electricity generated is lost through the transmission and distribution system. Technical losses within the transmission and distribution system accounted for 14% of electricity generated and 16% were unaccounted commercial losses. The remaining losses occurred in the transmission system. Upgrading transmission and distribution infrastructure would greatly address electricity generation concerns. Neighboring Albania recently transitioned from a similar level of technical and commercial losses in the distribution system improving from 38% total losses to less than 21% in 2014 with a goal of 15% in 2015 by integrating better meters (Ministry of Energy and Industry, *personal communication*).

Demand-side management emerges as one strategy that could alleviate theft within the distribution system and improve systems operability. The distribution company, KEK, has deployed over 30,000 smart meters, but this lags considerably behind the customer base of 400,000 individuals.

1.2.8 Natural gas development

Kosovo has no domestic natural gas resources for electricity generation. Currently, gas consumption and supply is limited to bottled liquefied petroleum gas. However, there are plans underway to construct the Trans Adriatic Pipeline (TAP) to deliver natural gas supply. We study the option of including natural gas by regional trade. Natural gas plants can facilitate the growth of solar PV and wind on the grid by providing peaking services in a cleaner and more efficient way compared to coal backup generation. Additionally, natural gas can diversify fuel supplies, and engage the country in regional markets. If combined with Kosovo's existing, but not yet implemented feed-In tariff policy, this use of gas, including biogas, can provide a scalable backstop resource that supports an overall path to expand the role of renewable energy deployment (Sitzmann, 2013).

Year	**Unit**		**Assumptions**	
			2010	**2015 (est'd)**
Capex	EUR/kW	Low	700	670
	EUR/kW	High	1200	1200
Fuel costs	MEUR/TWh	Low	27	25
	MEUR/TWh	High	27	30
Variable O&M	EUR/kWh	Low	0.1	
	EUR/kWh	High	0.1	
Fixed O&M	EUR/kW-yr	Low	20	20
	EUR/kW-yr	High	20	20
Life time	years	25		-
Construction time	years	3		
WACC	%	7%		
Cost of equity	%	-		
Cost of debt	%	-		
Debt ratio	%	-		
Capacity factor			89%	75%
Thermal efficiency	%		53%	56%

1.3 The Cost of Renewables

The cost of solar has reduced drastically over the past five years, due to photovoltaic-specific learning in the manufacturing sector. In Germany, for instance, the LCOE reached between 0.078 and 0.142 EUR/kWh. This represents an example lower-bound cost estimate based on electricity infrastructure improvements financed by KfW, the German development bank. We use the analysis from Fraunhofer, which applies an 85% learning curve to the levelized cost of solar electricity. The use of cost reduction improvements based on Germany's case will be an upper-bound estimate of the reduction in the cost of solar, since Germany outpaced other EU countries and Kosovo will need to undergo a series of technological learning. The potential for improvement in technological learning is highlighted by Germany's case.

Run-of-river mini-hydropower is estimated to generate electricity at 0.04 Euro/kWh, and the levelized cost of large-scale hydropower from Zhur is assumed at 0.10 Euro/kWh based on construction estimates (IEA, 2015). Domestic, on-shore wind and biomass projections are assumed to be 0.05 Euro/kWh and 0.06 Euro/kWh respectively (Fraunhofer, 2013). The cost of energy efficiency is derived from World Bank estimates as part of the Energy Efficiency and Renewable Project. We apply a 90% learning curve to wind and energy efficiency costs per year.

2.1.1 The Base case

The base case scenario considers the construction of Kosovo C, a 600 MW coal-fired power plant in 2017 to meet the generation gap induced by the closing of Kosovo A. The base case includes the continued operation of Kosovo B, including retrofits to extend its life-span beyond 40 years. We assume a 3% yearly improvement in transmission and distribution losses. The base case scenario includes imported electricity to continue due to reliability concerns. Recent explosions and technical problems at Kosovo A have severely limited production and forced Kosovo to increase imported electricity, therefore it is considered in this analysis. The cost of importing electricity is approximately 40 EUR/MWh. The base case scenario is highlighted in Figure 1.1. We project consumption based on estimated population and GDP growth, which is currently around 3% according to the World Bank.

2.1.2 Solar prices reduce to SunShot levels ($1/watt)

The second scenario considers the situation if the cost of solar PV reaches $1/W by 2020. The US Department of Energy established a program called SunShot solar power that strives to achieve this target. The progress so far indicates this is potentially viable and therefore we consider this an upper-bound scenario on the generation from solar photovoltaics. Reaching SunShot levels reduces the cost of solar to approximately 0.05 USD/kWh. This scenario also features the decommissioning of Kosovo A by 2017, and the expiration of Kosovo B by 2024 as it will reach 40 years of sustained use. The SunShot solar price scenario includes wind, electricity imports, biomass, the construction of Zhur, and run-of-river mini-hydropower. By 2020, this model reaches 325 MW of solar PV capacity.

2.1.3 Aggressive energy efficiency measures to reduce end-use consumption

The third scenario incorporates increased energy efficiency and a reduction in generation capacity due to reduced end-use consumption, meeting the Government of Kosovo's target of 9% improvement of energy efficiency by 2018. We apply a linear improvement in energy efficiency and assume that 1 kWh of energy conservation displaces 1 kWh of coal-fired generation from the baseload. There is great potential for energy efficiency measures across public buildings especially if considering the benefits of a nationwide building insulation campaign. The scenario, detailed in Figure 2.3, reduces consumption to nearly 5000 GWh by 2015. Also, this scenario considers significant investment and improvement in the transmission and distribution infrastructure to reduce losses by 50% from their current levels.

2.1.4. Introduction of natural gas

The natural gas scenario assumes that natural gas pipelines will facilitate the adoption of natural gas as a potential electricity generation source by 2018. While natural gas may only show modest improvement over lignite coal in terms of climate impacts, natural gas has significant advantages for grid operation in the presence of intermittent renewables. First, natural gas is more flexible to the variability of solar PV and wind. Secondly, the construction of natural gas facilities could potentially provide electricity without the magnitude of the public health costs associated with lignite coal. Natural gas prices in this scenario are based on Fraunhofer Institute projections of the fuel price to 2020 of 0.03 Euro/kWh. The inclusion of 600 MW of new gas capacity in 2019 could remove the need to extend Kosovo B beyond its current lifespan. This scenario includes the option for Kosovo to become a net exporter of electricity an in energy poor region, producing surplus electricity generation. In an open regional market, this could be a boon for the economy since Southeast Europe as the region remains energy poor.

2.1.5. Including storage cost for solar at high deployment levels

In this scenario, we apply a cost penalty for solar PV to add energy storage. This cost is attributed as 10% of the total system cost of generation and added to the cost for all solar PV. We add this to better represent the external costs that increased distributed solar resources may bring to the grid for balancing and flexibility. The storage penalty raises the cost of solar to reflect more conservative estimates. In this scenario pictured in Figure 2.6, we estimate far less solar PV developed compared to the scenario pictured in Figure 2.2. Additionally, we include expanded electricity imports to account for the difference in generation. The costs are detailed in Table 2 and the Appendix. The storage penalty scenario also includes natural gas to highlight the complementary role of natural gas as a flexible generator that fills in for intermittent renewables. The combination of flexible natural gas with solar PV, wind, and additional costs associated with energy storage presents an alternative that could satisfy electricity demand and create a net energy producing scenario.

2.1.6. Including a carbon shadow price

Adding a price on carbon changes the energy picture in several ways. First, we apply a shadow price of 30 EUR/ton CO_2-eq as practiced by the World Bank. This represents the price that World Bank uses to evaluate projects; therefore, we estimated our model using this level. Recent research into the social cost of carbon indicates that the full social cost of climate damages could even reach levels as high as $220 USD/ton CO_2-eq (~200 EUR/ton CO_2-eq) (Moore and Diaz, 2015). We assume that low-carbon electricity generation sources including solar PV, wind, hydropower, and imports will not receive any price on carbon. Imported electricity is excluded because we only count a carbon price within Kosovo. We apply this analysis in two ways. First we look at the additional cost of carbon added to the base case scenario when the generation mix consists predominantly of coal. The second application is applying the cost to coal and modeling a scenario where the carbon shadow price influences decisions to expand existing capacity. This scenario, pictured in Figure 5.6 requires the import of electricity to meet electricity demands in the later years. We would expect that a carbon shadow price further increases the gap between investing in future coal generation and alternative energy pathways.

2.1.7. Excluding gas and Zhur, but including a power exchange, and waste-to-energy

This alternative removes the possibility of including natural gas in the energy portfolio for Kosovo by 2018. The missing generation comes from participating in an open regional market and investing in new transmission capacity. This more conservative estimate also explores the possibility that construction delays for Zhur could prevent this hydroelectric source from coming online. This scenario relies on the continuation of Kosovo B beyond its expected lifespan.

3.2 Further details

We annualize the cost of generation each year in a net present value calculation to estimate the cost of the different scenarios until 2025. Appendix 1 details these cost figures.

The information on the potential for small hydropower developments comes from a previous feasibility study that highlights the potential for 63 MW of projects with projected annual production of nearly 300 GWh. The ERO office within Kosovo also foresees development of small-scale hydropower projects that could total up to 140 MW beyond 2020. We include this within our scenarios. We also analyze the potential construction of Zhur, where the development is proposed between Prizren and Dragash. However, we scale back the capacity of Zhur from the previous analysis due to the concerns over feasibility and include a scenario with an operation Zhur at 45 MW, which is 15% of the originally proposed capacity of 305 MW.

We introduce natural gas as one scenario by including the construction of the Trans Adriatic Pipeline (TAP) by 2018. Though natural gas remains politically questionable, it remains an important energy source globally and could become a large regional player given the supply shortages from other sources and regional market plans to trade gas. Additionally, recently the EU Energy Commission proposed an Energy Community Gas Ring, which would enable natural gas to play a role in the power sector and displace coal-generation. Regionally, in Albania, the conversion of a diesel plant to gas opens up the opportunity for future natural gas development in the region. Therefore, we investigate natural gas as a scenario for analysis among a range of alternatives.

The proposed construction of increased regional transmission capacity allows for future energy imports and exports and we also consider the potential for an open regional market via a power exchange. We include the construction of a 400 kV transmission line between Albania and Kosovo financed by the German Development Bank (KfW) in each scenario. The line is expected to be 241 km and cost approximately 75.5 million euros or 83 million USD (1 EUR = 1.1 USD). We use the cost of the expansion of transmission capacity in our estimation of the open regional market.

We estimate transmission losses based on the USAID energy efficiency reports and figures from KOSTT, the Kosovar transmission system operator. The KOSTT system already interconnects with Montenegro (400 kV line), Macedonia (400 kV line), Albania (220 kV line), and Serbia (400 kV, 220 kV, and 110 kV) allowing transit, imports and exports of electricity. The existing interconnections provide key opportunities for future electricity trading in an open regional market situation.

The demand forecasts are based on KOSTT information and public reports (KOSTT, 2011). The future expected demand incorporates projected population growth and economic growth by using GDP. We assume 3.2% growth in GDP per annum. This version of the model does not incorporate seasonal fluctuations for hydropower or demand requirements on peak time scales. However, it provides a picture of different ways Kosovo could meet demand, especially given severe supply constraints.

We use energy efficiency costs from the most recent USAID report and the newly funded Kosovo Energy Efficiency and Renewable Energy project funded by the World Bank that aims to reduce energy consumption in public buildings (USAID, 2013). The household and services (public and private) building sectors account for approximately 48% of final energy consumption in Kosovo (World Bank, 2013). The Government of Kosovo's energy efficiency target of 9% reductions by 2018 falls short of the EU's 20% reduction requirement. Our energy efficiency scenario considers meeting the Government of Kosovo's energy efficiency target of 9% improvement by 2018. If Kosovo seeks accession to the EU, the energy efficiency targets would need to increase to reflect EU directives on energy, the environment, and market competition (USAID, 2013).

Kosovo experiences severe losses across the distribution system, which is now privatized and operated by a Turkish consortium called "Limak-Calik." Koorporata Energjetike e Kosoves

(KEK), the previous company that maintained the distribution system is only responsible for energy production. Technical losses on the distribution system have ranged as high as 16% in one year due to outdated equipment, a lack of maintenance, and network inefficiencies.

Furthermore, including a price on carbon widens the difference in cost between the studied scenarios because of the carbon intensity of lignite coal. Therefore, a shadow price on CO_2 emissions further pushes the base case scenario from the range of alternatives in terms of total estimated cost.

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Chapter 2: Trace metal content of coal exacerbates air pollution-related health risks: the case of lignite coal in Kosovo

Abstract

More than 6,600 coal-fired power plants serve an estimated five billion people globally and contribute 46% of annual CO_2 emissions. Gases and particulate matter from coal combustion are harmful to humans and often contain toxic trace metals. The decades-old Kosovo power stations, Europe's largest point source of air pollution, generate 98% of Kosovo's electricity and are due for replacement. Kosovo will rely on investment from external donors to replace these plants. Here, we examine non-CO_2 emissions and health impacts by using inductively-coupled plasma mass spectrometry (ICP-MS) to analyze trace metal content in lignite coal from Obilic, Kosovo. We find significant trace metal content normalized per kWh of final electricity delivered (As (22.3 +/- 1.7), Cr (44.1 +/- 3.5), Hg (0.08 +/- 0.010), and Ni (19.7 +/- 1.7) mg/kWh_e). These metals pose health hazards that persist even with improved grid efficiency. We explore the air pollution-related risk associated with several alternative energy development pathways. Our analysis estimates that Kosovo could avoid 2,300 premature deaths by 2030 with investments in energy efficiency and solar PV backed up by natural gas. Energy policy decisions should account for all associated health risks, as should multi-lateral development banks before guaranteeing loans on new electricity projects.

1. Introduction

There is increasing global debate on the sustainability of coal as a source of electricity.[1,2,3] In Europe and the United States, low-cost renewable energy options such as solar and wind, along with the natural gas revolution, have led to a rapid closure of coal plants. In other regions, however, coal is experiencing a renaissance, [4] with increasing proposals for new plants across South and Southeast Asia. In South East Europe, coal use remains contentious because of (1) the role played by multi-lateral development bank finance, (2) rising concerns over air quality, and (3) planning for potential future European Union integration.[5,6] The use of locally abundant lignite coal in subcritical coal plants without substantial pollution control technologies, violates the EU Industrial Emissions Directive and could jeopardize admission to the EU.[7] Coal is becoming increasingly difficult to justify on an economic basis.

Coal has been the dominant energy source around the world since the industrial revolution and is responsible for a significant proportion of greenhouse gas emissions and air pollution-related deaths worldwide. In total, coal currently contributes 46% of annual global CO_2 emissions.[4,8] Associated fine particulate matter (PM) emissions and toxic air contaminants contribute significantly to the burden of disease from air pollution.[9] However, the majority of health-effects studies focus on the magnitude of PM emissions and have not applied source-specific information to risk calculations.[10,11,12] Even in countries where emissions-accounting is relatively transparent, trace metal emissions remain unaccounted for in PM indices, despite their established presence in geologic coal analysis.[13] Investment decision frameworks rarely consider emerging research that implicates hazardous air pollution and PM emissions in the global burden of disease.

Kosovo, a country on the verge of implementing a suite of new supply- and demand-side electricity investments, currently relies on lignite coal for more than 98% of its electricity generation. Although lignite has the lowest quality and calorific value of all coal types, its local abundance explains its continued use. The World Bank has proposed financing a new lignite coal-based power plant to replace the scheduled decommissioning of the 1962 era lignite-based "Kosovo A" facility and to address the security of Kosovo's electricity supply. The plan would continue to use lignite coal as a fuel source and improve efficiency with newly available technology. This is proposed as a means to improve electricity reliability and air quality, as power plant efficiency gains could marginally reduce air pollution.

While all coal produces hazardous emissions when combusted, impurities in lignite coal present significantly greater threats to human health and the environment compared to other coals.[11] However, little information is publically available regarding the trace metal content of Kosovo's lignite supply or its associated public health impacts. Research into the composition of lignite coal, both globally and specifically in Kosovo, could inform more comprehensive evaluations of the environmental and health impacts of fossil-fuel based electricity generation.[14] It could also identify opportunities to reduce illness and premature deaths by switching to alternative sources of electricity.

Due to the widespread use of coal for electricity production, scientists still need more geographically specific information on trace metal content. Here, we investigate the chemical composition of lignite coal from Obilic, Kosovo (the main lignite coal mine located 12 km outside of the capital city, Pristina, and the primary coal source in Kosovo). Using inductively-coupled plasma mass spectrometry (ICP-MS), we characterize the identity and hazardous trace metal content. We propose a new metric of *trace metal content per final unit of electricity delivered*. Aerosolized arsenic, nickel, and other trace metals in particulate matter are typically difficult to quantify, especially in regions that lack significant air monitoring and sensing equipment. These heavy metals are also present in fly ash. Our metric enables scientists and investors to understand the geographic differences in coal content, which may alter the emissions profile projected for new energy projects.

Coal studies have typically analyzed the chemical composition of higher density bituminous and anthracite coals, demonstrating the presence of hazardous metals. Arsenic, cadmium, chromium, mercury, nickel, selenium, and lead have been detected in bituminous coal samples from the United States and Brazil.[15,16] By contrast, few studies investigate the chemical composition or emissions from lignite coal. Despite lignite coal's relatively low energy density, local availability leads many countries to depend on lignite, including those in South East Europe. Countries in Southeast Asia, including Vietnam and Indonesia, plan to increase combustion of lignite coal for electricity generation.[12,17,18] Continued investment in lignite by multinational finance organizations influences global patterns of energy production and consumption, yet they so far fail to consider geographic differences in the chemical composition of coal, or account for its public health impact. Global estimates suggest coal combustion is responsible for 2-5% of total anthropogenic arsenic emissions.[19] In the US, coal-fired power plants contribute approximately 62% of arsenic, 50% of mercury, 28% of nickel, and 22% of chromium emissions.[20] These toxic heavy metals harm the environment and human health.

Although previous studies have identified externalized costs of burning coal for electricity generation, there is relatively little data on the impact on human health of trace metals released through combustion.[11,12,21,22]

We investigate the trace metal content (arsenic, mercury, chromium, and nickel) in Kosovo lignite coal. We present this information alongside estimates of annual PM emissions. Since trace metal content is not currently accounted for in estimates of premature death attributable to air pollution, these estimates likely under-count the actual health toll of coal combustion. Therefore, our analysis could inform further research.

Human health impacts of trace metals

Power plants remain one of the largest sources of toxic air emissions, including metals[11,23,24]. People can be exposed to trace metals in particulate matter through inhalation, ingestion, and dermal contact. Recent studies highlight the disproportionate impacts of toxic air pollution on low-income children, linking cumulative exposures to toxic air pollutants with adverse effects on the developing fetus including preterm births, low birth weight, cognitive and behavioral disorders, asthma, and respiratory illness.[25] For example, once arsenic enters the environment, it cannot be destroyed, so any effects will persist until the arsenic becomes chemically isolated from the biosphere. Arsenic is a known human carcinogen –irrespective of exposure route—and is particularly linked to lung cancer[26]. Arsenic can also cause several skin disorders and can reduce immune function by decreasing cytokine production.[27] Toxic heavy metals have long residence times and tend to bioaccumulate in the human body. For example, it may take a few days for a single, low dose of arsenic to be excreted, and mercury has an estimated half-life in the human body of around 44 days.[28,29] Continuous or daily exposure in the context of relatively slow elimination translates into steadily increasing tissue concentrations of these toxic metals.

In adults, chronic mercury exposure can produce tremors, cognitive dysfunction, and other nervous system dysfunction. However, the most harmful effects of mercury exposure occur in the developing fetus. Even at low concentrations, prenatal mercury exposure can decrease IQ and cause long-term cognitive impairment, depending on timing and extent of exposure.[30] Prolonged inhalation of mercury vapor in adults can lead to pneumonia, corrosive bronchitis, and tremors. Increasingly, governments around the world have incorporated mercury emissions into standards for reducing emissions of toxic air contaminants, as power plants serve as the dominant source of mercury in air pollution. Despite this trend, and despite proven pollution control technologies to limit mercury emissions, relatively few governing bodies set standards or limit mercury from power plants.[31]

Coal combustion is one of the major anthropogenic sources of chromium air pollution.[23] Chromium (VI) is the most hazardous valence state; hexavalent chromium is a known carcinogen and causes both developmental and reproductive toxicity. Some occupational studies attribute decreased sperm count and quality to chromium (VI) in exposed workers.[32] Furthermore, chromium can have synergistic effects with other organic carcinogens, and mixed exposures can increase the risk of certain cancers.

One of the most common forms of allergic dermatitis is nickel dermatitis caused by exposure to nickel-containing compounds. Additionally, inhalation of high levels of nickel increase the risk of lung and nasal cancer.[33]

Table 1 summarizes environmental and human health impacts from trace metals found in lignite coal samples. It also describes solubility in water and boiling point for arsenic (III or V), chromium (0, II, III, and VI), mercury (II), and nickel (II). Solubility and boiling point are important to determine whether the metals will undergo phase changes during power plant combustion. The boiling point of arsenic trioxide is approximately 465° C, which is within the range of a standard boiler in a coal plant, leading to volatilization of arsenic, which could aerosolize within particulate matter.

Table 1. Trace metals present in lignite coals and their associated environmental and health impacts.

Heavy Metal (CAS #)[32]	Arsenic (7440-38-2)	Chromium Metal, Chromium (II), Chromium (III), Chromium (VI) (7440-47-3)	Mercury (7439-97-6)	Nickel (7440-02-0)
Environmental Impact	-Contaminates groundwater -Disrupts plant growth and development -Decreases crop yields	-Increases uric acid concentration in birds' blood -Alters animal growth	-Impairs nervous system and other organ systems in animals	-Causes genetic alterations in fish and possible death -Toxic to developing organisms
Human Health Impact	-Impairs immune system, increasing susceptibility to lung cancer	-Causes reproductive and developmental harm -Increases risk of certain cancers	-Causes cognitive impairment in children -Overstimulates central nervous system	-Increases risk of lung cancer -Causes nickel dermatitis
Boiling Point (ºC)	465	2482	357	2730
Solubility in Water (g/L)	20 (arsenic trioxide) at 20 ºC	1680 (chromium trioxide) at 25 ºC	74 (Mercury II chloride) at 25 ºC	553 (nickel chloride) at 20 ºC

2. Methods

Analysis of trace metal content per final unit electricity delivered

We obtained 50 g samples of Pliocene lignite coal found in the Kosovo basin located at the main coal mine in Obilic, Kosovo (within a 5-km radius of 42.689° N, 21.069° E, SI Figure S1). Trace metals analysis by inductively coupled plasma mass spectrometry (ICP-MS) was conducted by Curtis & Tompkins Laboratory (Berkeley, CA) according to EPA standard procedures appropriate for each metal. Sample preparation was performed by EPA method 3052, and then EPA method 6020 was used for the detection of for aluminum, arsenic, beryllium, cadmium, chromium, copper, lead, nickel selenium, silver, thallium, and zinc and EPA method 7471A for mercury (see Supporting Information).[34,35,36]

Using the measured trace metal content in lignite samples, we estimate the trace metal emissions by creating an "emissions factor". The emissions factor is defined as the mass of trace metals (in mg) emitted from coal combustion per kWh of final electricity delivered (see SI Equation 1). To do this, we developed an open-source spreadsheet model to evaluate the trace metal content per kWh of final electricity delivered at different transmission, distribution, power plant efficiencies, and heat rates. We input ICP-MS results of trace metal content and known calorific values (kJ/kg) of different coal types into the model. The model parameters include generation, transmission, and distribution system efficiency of electricity (n_t, n_d), calorific value of coal (kJ/kg), and efficiency and heat rate of the coal-fired power plant. We use literature-cited data for international global average trace metal content and literature values for Chinese coals[37,38,39]. The model calculates a unit conversion from measured trace metal content (mg/kg) into trace metals per unit electricity (mg/kWh_e) based on plant characteristics such as heat rate and efficiency. This metric enables fair comparisons of the potential impacts of trace metal emissions across different countries' coal generation, transmission, and distribution systems by accounting for the relative energy densities of different coal types and the efficiencies of different plants and electric transmission and distribution systems.

We also use the spreadsheet model to compare the trace metal content in Kosovo coal with reported mean trace metal content (and standard deviation values) from global datasets. Although it is not a spatially explicit chemical fate and transport model, it provides a reasonable range estimate of the release of trace metals at the smokestack, while taking into consideration the local generation, transmission, and distribution system conditions that may increase emissions intensity.

During coal combustion, trace metals are distributed among flue gas, bottom ash, and fly ash. We use trace metal mass balances and estimate that 1-10% of As, Cr, and Ni will appear in flue gas, based on estimates in the literature. Mercury is evaluated separately since it is more volatile, with 80% of mercury appearing in flue gas.[40,41] The general model for estimating trace metal content per final unit of electricity delivered and trace metal partitioning is detailed in the Supporting Information.

We report mean, standard deviation, and lower-upper bound ranges for mg of trace metals per kWh of final electricity delivered. After estimating the emissions factor for each individual trace metal, we can also estimate system-wide emissions from electricity generation:

$$E = \sum_k \sum_m A_{i,k} * EF_{i,k,m} \qquad (1)$$

where E = emissions, k = the fuel type, m = the emissions control devices, and i = the power plant

This framework investigates the potential to reduce environmental health impacts by improving power plant and grid efficiency.

Estimation of air pollution-related health risk

In addition to estimating trace metal content per final kWh of electricity delivered (the emissions factor), in a separate analysis we use an energy systems model that evaluates the cost of possible future electricity scenarios to estimate air pollution-related health risk attributable to the air pollutants associated with each scenario. This provides context for systems scale risk analysis. We can also use the energy systems model to estimate systems-level trace metal content that could be released into the environment in each scenario of future energy sources. Figure 1 shows the overall approach and how these analyses are conducted independently and used to support each other.

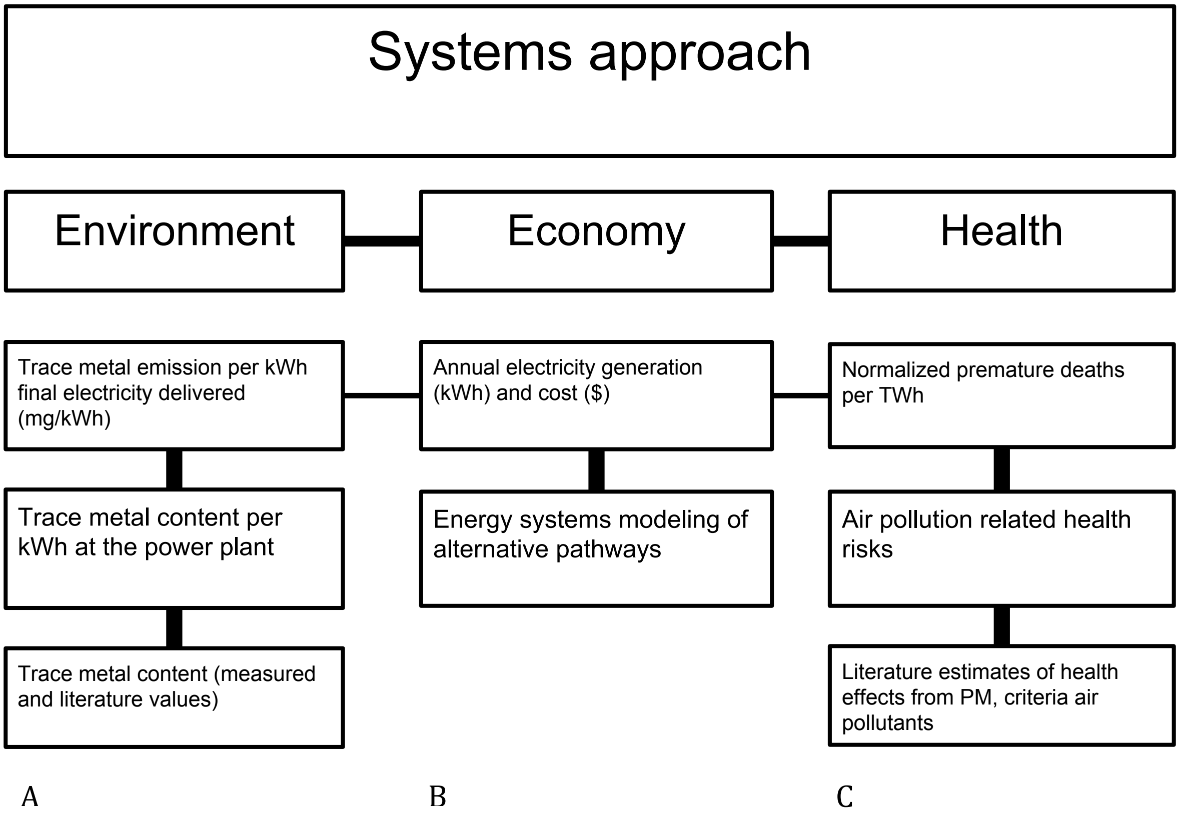


Figure 1. Overall approach of the three parallel analyses that evaluate environmental (A), economic (B), and health (C) impacts of lignite coal in Kosovo.

To analyze the air pollution-related health risk from a variety of future electricity portfolios, we use four representative annual electricity generation scenarios developed by a stakeholder analysis in consultation with civil society and lending partners. Following the model established in Kittner et al. (2016), we compare the associated environmental and public health risks (from air pollution and trace metals) for each scenario.[17] We investigate a corresponding business-as-usual case, evaluating the net costs of: (1) constructing a new lignite plant, (2) using energy efficiency measures to meet Euro2030 targets (3) transitioning to low-cost solar without natural gas backup, and (4) using solar augmented by natural gas for system flexibility. For a full detailed evaluation of the spreadsheet model, the associated paper describes the model and assumptions used for analyzing Kosovo's power sector.[17] For scenarios that include natural gas, solar, and wind, we use the same values for health and environmental impacts of these technologies as reported in the literature for continental Europe.[42]

The annual electricity generation portfolio values (kWh) are then applied to an occupational and air pollution-related risk methodology called ExternE: Externalities of Energy.[42,43] The ExternE model predicts health impacts attributable to air pollution and occupational risks for each energy technology scenario expressed per kWh. The ExternE model accounts for reduction in life expectancy and cancers, e.g., premature death. The premature death endpoint estimates excess mortality attributable to exposure to $PM_{2.5}$, sulfur dioxides, nitrogen oxides, and ozone.

3. Results

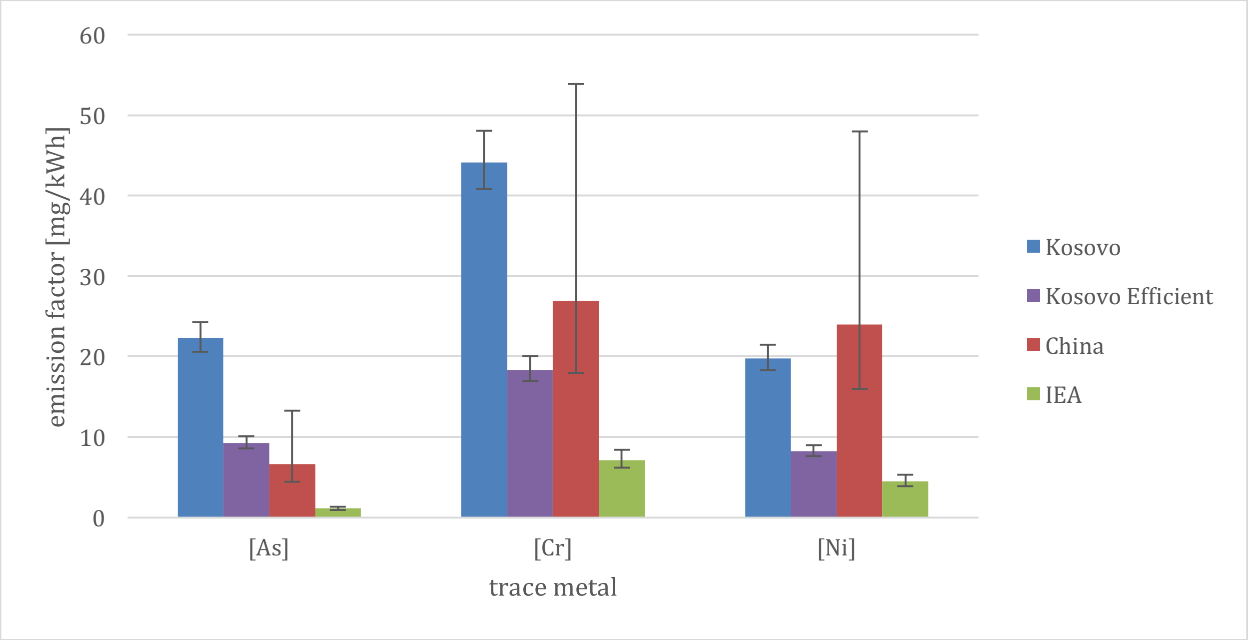
We present the results in two parts. First, we report the trace metal content analysis represented in Figure 1A, and we report the results from Kosovo alongside trace metal content of lignite coal in China and globally (based on IEA data) to put the numbers into perspective. Second, we use energy systems modeling represented by Figure 1B as inputs to show premature deaths represented by Figure 1C. Finally, we discuss the results.

Table 2 contains the results of ICP-MS trace metal analysis for lignite coal in Kosovo compared to (1) average trace metal content in a cross section of lignite coal globally (IEA), and (2) trace metal content reported in the literature for lignite coal in the US and China.[37,38,39]

Table 2. ICP-MS Heavy Metal Content in Kosovo Lignite Compared to Lignite from Other Regions
All values are in mg metal/kg coal.

Heavy Metal	Content in Kosovo Lignite Coal	International Energy Agency Global Average	Content in coals from China[38,39]		Content in coals from USA[37]		Content in coals around the world[37]
			Bai et al. (2007)	Dai et al. (2012)	Arithmetic mean	Geometric mean	
Arsenic	9.6 ± 1.6	2.69	4.09	3.79	24	6.5	8.3
Chromium	19 ± 1.7	17.6	16.94	15.4	15	10	16
Mercury	0.035 ± 0.020	0.091	0.154	0.163	0.17	0.10	0.10
Nickel	8.5 ± 1.7	11.1	14.44	13.7	14	9	13

Figure 2 reports the trace metal content per final unit of electricity delivered in kWh (reported in mg/kWh). This only includes metal content in the flue gas. We simulate the existing Kosovar grid with 30% transmission and distribution losses (represented by "Kosovo") and compare to an improvement to only 10% losses, which represents an upper bound for typical transmission and distribution efficiency ("Kosovo Efficient" in Figure 2). Additionally, we estimate the normalized trace metal content per unit electricity delivered in China and globally (IEA estimate) for lignite coals with transmission and distribution efficiency of 10% to account for line losses, de-rating, and congestion.[44] These are reasonable upper bound estimates based on EIA transmission and distribution losses data.[45,46] We find that even if Kosovo significantly improves transmission and distribution systems, the poor quality of the lignite coal means that trace metals emissions will still be significantly higher than they would be for a coal source on par with the IEA average metal content in global lignite.



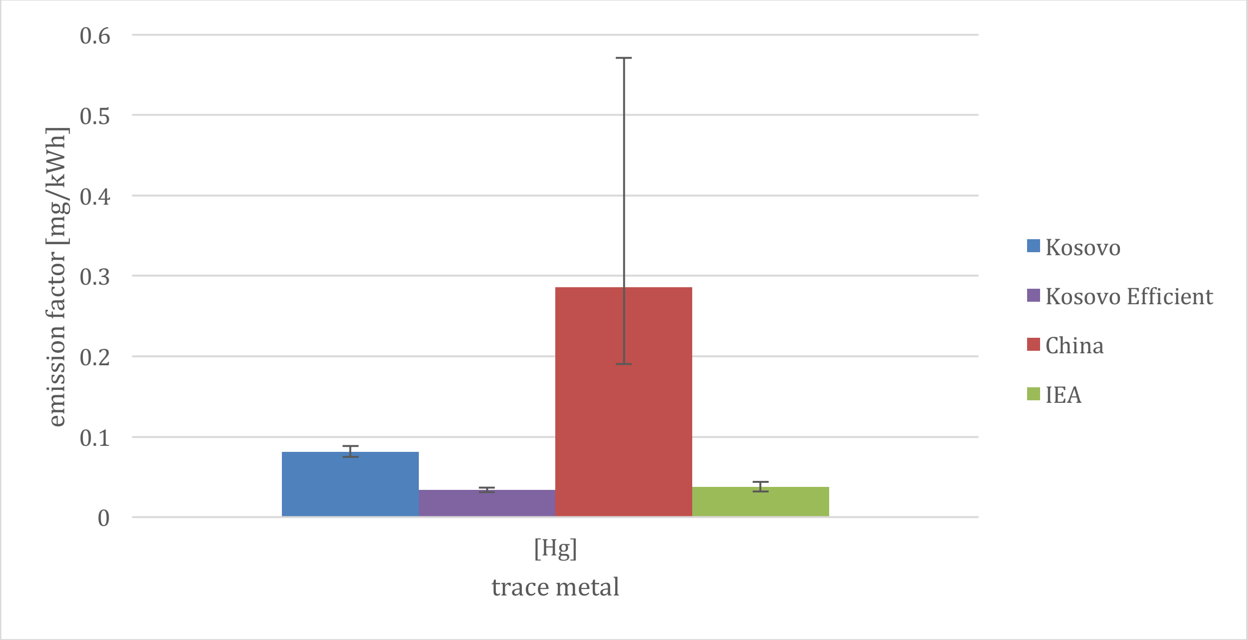


Figure 2. Trace metal emissions for [As], [Cr], [Ni], [Hg], expressed per kWh final electricity delivered by country. Variation in China is likely due to significant diversity in reported mercury content in lignite that spans multiple geologic basins.[39]

We find high arsenic and chromium content compared to IEA average values for lignite in the ICP-MS analysis. The mercury (0.08 mg/kWh [Hg]) and nickel (19.7 mg/kWh [Ni]) content, while lower than the Chinese average values for lignite (0.28 mg/kWh [Hg] and 24 mg/kWh [Ni]), may pose public health concerns to the nearby Kosovo community. This raises concerns for fly ash management and also aerosolization of trace metals with particulate matter emissions.

Accounting for health

Table 3 highlights the deaths from air pollution-related risk calculated for different energy technologies following the ExternE method detailed by Markandya and Wilkinson.[42] The model assumes a population density of 160 people/km^2, based on Kosovo. The model characterizes pollutants of different electricity technologies based on inputs of annual electricity generation (total kWh), and it only considers health impacts for coal and natural gas (based on emission of PM_{10}, $PM_{2.5}$, SO_x, NO_x, O_3). It does not include source-specific trace metals in the PM burden, similar to the current version of USEtox.[9,47] One limitation in the ExternE model is the assumption of a linear relationship between $PM_{2.5}$ exposure and premature death. Research in the past decade suggests that at low background concentrations of $PM_{2.5}$, the concentration-response relationship is supralinear.[48] However, in this case a linear relationship is the best estimate given that (1) background PM levels are high enough to appear in the linear portion of the concentration-response curve, (2) there is limited empirical data available to use more sophisticated models, and (3) our knowledge of local geography that concentrates pollution in a valley in Kosovo. An alternative approach could use TRACI, a model developed by the EPA.[49-51] However, TRACI is not explicitly set up for power plants as was ExternE and it is generic (using non-speciated metals) for metal species. TRACI is also intended for the US. In this instance, relying on TRACI would compound the uncertainties of this model. Future updates to USEtox and TRACI would allow for research on the specific health impact of trace metal species in the PM burden, but the current versions have not yet accounted for speciated composition of trace metals in the PM burden.[47] SI Table S5 details existing annual air pollutant emissions.

Table 3. Air pollution-attributable morbidity and mortality in four energy scenarios evaluated in Kosovo's power sector projected for 2016-2030.

	Air pollution-related risk	-	-
	Deaths	**Serious illness**	**Minor illness**
Business-as-usual	**3,200** (800-12,700)	**29,000** (7300-88,000)	**1,700,000** (430,000-6,900,000)
Euro2030	**2,000** (510-8100)	**18,500** (4,600-75,000)	**1,100,000** (280,000-4,400,000)
Solar without natural gas	**1,300** (320-5,200)	**12,000** (2,900-47,000)	**700,000** (180,000-2,800,000)

Solar with natural gas	**900** (230-3,600)	**8,400** (2,100-33,700)	**460,000** (120,000-1,800,000)

The death rates are expressed as mean estimates with 95% confidence intervals. While the model includes acute and chronic health effects, chronic health effects account for between 88-99% of the total impact. Serious illnesses (acute and chronic) includes cerebrovascular events, congestive heart failure, and chronic bronchitis. Minor illnesses include restricted activity days, bronchodilator use, persistent cough, and lower-respiratory symptom days for those with asthma. We adapt the model to the Kosovo case using scenarios from Kittner et al. (2016) and we aggregate excess risk of deaths over the projected period from 2016-2030.[17] Full annual electricity generation mix until 2030 of the scenarios analyzed is detailed in the Supporting Information (SI Figures S2-5). Additionally, the Euro2030, solar without natural gas, and solar with natural gas to each cost less than the business-as-usual scenario by €200-400 million euros before considering health and environmental externalities. The population of Kosovo is only 1.8 million and this model shows 1.7 million cases of minor illnesses in the business-as-usual case. Business-as-usual coal includes the use of the best available pollution control technologies.

4. Discussion

The scenarios depicted demonstrate that there is a range of future cost-competitive paths for the electricity sector in Kosovo. Kittner et al. (2016) finds the alternative scenarios to coal-based power generation to cost less on a direct levelized cost basis before considering externalities. This study takes the next step to identify and estimate some of the public health risks that better characterize the overall cost of each scenario accounting for all externalities. Interestingly, natural gas, which produces less PM pollution, may provide public health benefits compared with lignite coal, although it could have the consequence of delaying substantial reductions in CH_4 or CO_2 emissions. In the other scenarios, low-cost solar and energy efficiency alone would mitigate air pollution related-risk, though not to the same extent as the scenario that combines these two interventions with natural gas. The scenarios without natural gas rely on continued operation of the Kosovo B coal-fired power plant for base-load power generation. Emerging low-cost energy storage technologies or increased regional power trade could change this result in ways that are not detailed in this analysis.[51] They could also reduce the use of coal in the energy efficiency and renewable scenarios that do not employ natural gas. One clear outcome remains: sustained use of lignite coal poses serious air pollution-related risk and an introduction of natural gas and/or renewables to provide flexibility in Kosovo's grid could meet future electricity needs while providing a cleaner and safer alternative to lignite coal. It is possible to incorporate health risk in addition to cost when comparing electricity development pathways.

At full operating capacity, the Kosovo A and B facilities consume 30,000 tons of lignite coal per day. In 2005, the CO_2 emissions were estimated at 5.7 million tones. SO_x emissions exceeded European Commission standards by 333 ug/m^3 and PM emissions exceeded by an order of magnitude (SI Table S5).[52] These results suggest that coal contributes significantly to air pollution. Air pollution also contributes to premature mortality, and a significant portion of the air pollution in Kosovo is attributable to lignite coal. A replacement of coal infrastructure with natural gas could reduce thousands of air pollution-related illnesses and deaths in the coming decade. The renewable scenarios may also dramatically reduce CO_2 emissions. The lack of low-NOx boilers or other pollution control technologies on Kosovo's power plants means that our model likely underestimates the impact of air pollutants which form when power plant emissions undergo chemical oxidation. The scenario where solar is introduced without gas demonstrates that potential public health benefits of solar power and energy efficiency will be attenuated if coal remains a significant source of base-load power generation. Emerging energy storage technologies could change this result. We project that a full-scale transition away from coal or natural gas would reduce air pollution-related risk by the largest increment, however Kosovo B lignite power station is expected to remain in operation through 2030.

There are significant short and medium-term public health benefits to switching from coal to gas. However, natural gas may raise implementation challenges due to a lack of domestic supply.[17] The flexibility afforded by the addition of natural gas to power system operations could also provide load balancing for intermittent solar and wind in the case that planned regional interconnection projects are delayed or are subject to political turmoil. It may seem counterintuitive to propose natural gas as a stopgap solution, given the lack of defined climate benefits, however the cost of continued lignite coal combustion that we estimate in the form of predicted air pollution-related deaths in Kosovo merits this transition.

Particulate matter, specifically PM_{10} and $PM_{2.5}$, accounts for about 3% of cardiopulmonary and 5% of lung cancer deaths worldwide, and the burden of disease related to similar ambient air pollution may be even higher.[53] Heavy metals, like the ones studied in this paper, could contribute not only individually but also synergistically to the toxicity of particulate matter released from the coal combustion process, although local monitoring of metal content and emissions could help verify our modeled estimates. We suspect ours are underestimates because our tests of Kosovo lignite reveal higher trace metals content than the coals on which most models are based except for mercury. Arsenic in fly ash is a source of groundwater contamination.[54] Nickel, chromium, and mercury can increase the risk of developing certain cancers, especially for vulnerable populations like children and those who already have asthma or chronic obstructive pulmonary disease.

In the short term, a few remedy measures could potentially reduce air pollution-related risk due to trace metal presence in lignite coal. These include installation of flue gas desulphurization units, electrostatic precipitators and fabric filter for PM less than ten microns. Additionally, low-NOx boilers or selective catalytic reduction (SCR units) could reduce NO_x emissions. However, the largest health impact would come from shutting down Kosovo A and transitioning to a more sustainable power sector that does not include combustion of lignite coal. The cost and availability of low-pollution alternatives including solar photovoltaics, wind, biomass, and small-scale hydropower could meet electricity generation needs while dramatically reducing impacts on public health and the environment.[55]

The trace metals found in pre-combusted lignite coal in Kosovo are only one aspect of the overall public health threat. Coal-fired power plants release a variety of pollutants—particulate matter, sulfur dioxide, nitrogen oxides, heavy metals and radionuclides—that in this case likely contribute to thousands of premature deaths in Kosovo over the next decade. Simply increasing efficiency of current energy production and distribution systems is not enough to protect public health because the same coal is still being burned—burning a higher grade coal could reduce chemical emissions slightly, but is unlikely to significantly reduce the public health impact of particulate matter emissions. For this reason, stakeholders should prioritize sustainable energy scenarios that reduce dependence on coal. This does not detract from the value of improving energy efficiency on the demand side, or by improving energy transmission and distribution, but it highlights that substantial upgrades in the existing infrastructure should have the goal of reducing health impacts of the electricity supply source. Our research illustrates that the chemical composition of pre-combusted coal is a critical factor to consider when modeling human and environmental health impacts of electricity generation.

We recommend that multi-lateral development banks incorporate public health risk analysis into their finance decision-making frameworks to reflect emerging research on the global burden of disease caused by energy production—particularly coal-fired power plants. Most international financial institutions are not required to carry out a public health risk analysis prior to investment. We find that, for example, introducing natural gas for system flexibility could also reduce premature deaths attributable to particulate matter exposure as well as potential health risks from exposure to the toxic metals present in emissions from lignite coal combustion. Finally, we advocate for a reappraisal of financing options for a coal-fired power plant in Kosovo, as renewable electricity options are not only less expensive, but could also improve the poor local air quality and reduce air pollution-related premature deaths.[17]

A better monitoring framework for PM emissions from lignite coals could improve environmental and public health outcomes because the current risk assessment framework does not account for the actual composition of particulate matter. Determining the trace metal content at the same time as $PM_{2.5}$ and PM_{10} concentrations are assessed would more accurately reflect current research on the environmental and human health impacts of toxic metals in air pollution. Since the toxicity of common trace metals is relatively well characterized, understanding the relationship between the composition of particulate matter and the health hazards posed by toxic air contaminants is a critical topic for future research.[56]

Further research into the composition of lignite coal used for energy production and its unintended impacts on human health could help countries or regional entities conduct integrated resource plans for future energy infrastructure that account for population health. Information on the impact of trace metals in coal could improve decision-making by energy planners, and the international institutions that finance large infrastructure projects. Additionally, such information could help address the challenges of coal-based electricity generation projects identified by justice-based and legal frameworks, such as the need for due process, sustainability, and intra- and inter-generational equity, especially given the historical legacy of Kosovo C.[57]

The arsenic and chromium content we measured in samples from the Kosovar Pliocene basin exceed global IEA averages for lignite. There is cause for concern that these metals, as well as other toxic metals like the mercury and nickel also found in the lignite coal samples, are not currently accounted for in PM emission risk assessments and could negatively impact public health by increasing the surrounding community's risk for neurodevelopmental impacts, respiratory illness, cancers, cardiovascular disease, neurological impairment and premature death. Our modeling indicates that the continued use of lignite coal is detrimental to public health. Even if solar costs in Kosovo reach US SunShot levels (US$1/W) or aggressive energy efficiency measures are adopted, coal must be phased out to address the known public health impacts of air pollution. Substituting natural gas for lignite coal electricity could improve public health, however, it may not reduce carbon emissions in a similar manner. Before financing a new coal-fired power plant in Kosovo that burns lignite coal, international financial institutions should account for air pollution-related public health risk and additional burdens.

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Supporting Information: Trace metal ICP-MS analysis, models, and further documentation of results are presented in the Supporting Information.

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Supporting Information for:

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APPENDIX:

Methods for trace metal content analysis:

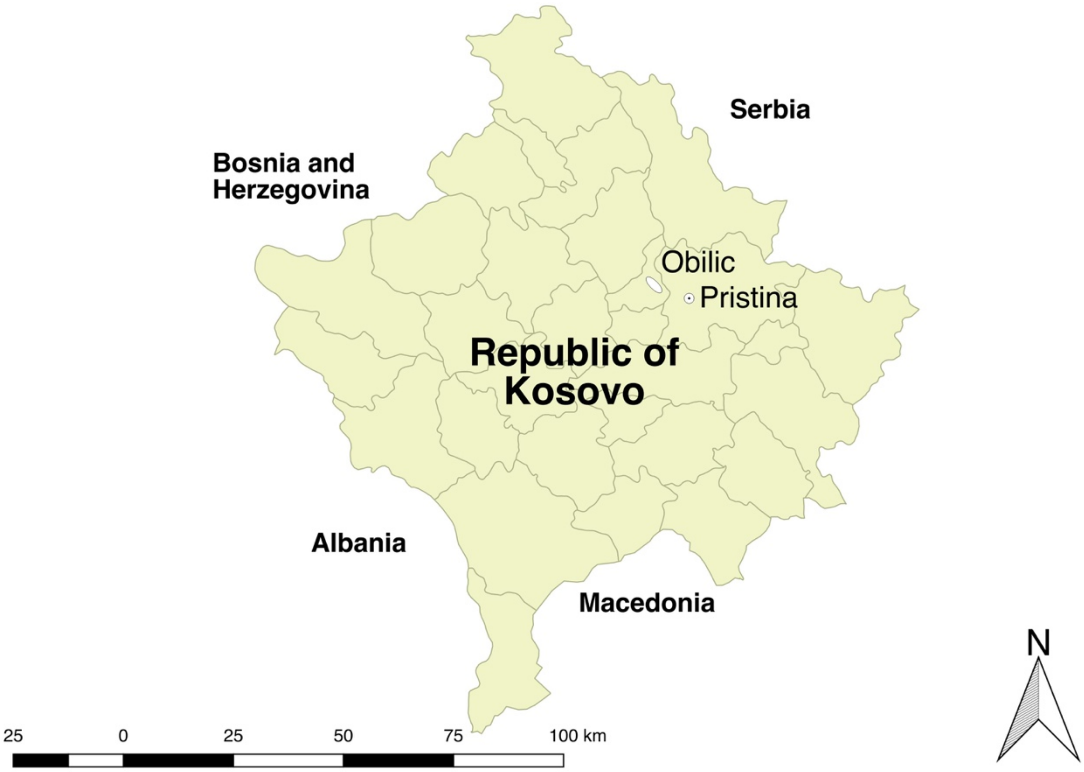


Figure S1. Map of lignite coal mine in Obilic, Kosovo located 12 km from Pristina.
Coal samples were taken within a 5-km radius of 42.689° N, 21.069° E. Figure S1 was created using administrative boundaries from European Environment Agency and QGIS.[1,2]

Mercury: EPA Method 7471A
Cold-Vapor Atomic Absorption Spectroscopy
The sample was first digested with aqua regia. Mercury, a liquid at room temperature, was aerated (evaporated) out of the sample and passed to a cell in an atomic absorption spectrometer. Light is passed through the cell, and the amount of light absorbed is proportional to the amount of mercury in the sample. A mercury lamp is used as the light source, as it produces radiation of the same wavelength at which the mercury atoms in the cell absorb.

Other Metals: EPA Methods 3052 and 6020
HF Digestion and Atomic Emission Spectroscopy
The sample was digested according to Method 3052, where a strong oxidizer, hydrofluoric acid and microwave radiation are used to completely dissolve the sample in water. The solution of metal cations was then analyzed by an Inductively Coupled Plasma Atomic Emission Spectrometer. The solution is injected into argon plasma at greater than 6000 C, atomizing the sample and exciting the metal ions. When the excited ions return to their unexcited state, they emit light at a unique wavelength and at an intensity proportional to the concentration of that metal in the sample, which is measured by a detector.

In both methods, the instruments were calibrated against metal solutions of known concentration. Reagent blanks, laboratory control samples and spiked samples were used by the laboratory to ensure that no trace metals were lost in the process before detection and that the detection signal was not affected by interferents.

Table S1. Comprehensive table of inductively coupled plasma mass spectrometry results of all tested primary pollutant metals. The unit measure for the results and reporting limit columns is mg/kg.

Analyte	**Result**	**Reporting Limit**	**Dilution Factor**	**Batch #**	**Prepared**	**Analyzed**	**Preparation Technique**	**Analysis Method**
Antimony	Not Detected	1.8	100.0	227295	09/17/15	09/18/15	EPA 3052	EPA 6020
Arsenic	9.6	1.6	100.0	227295	09/17/15	09/18/15	EPA 3052	EPA 6020
Beryllium	Not Detected	1.1	100.0	227295	09/17/15	09/18/15	EPA 3052	EPA 6020
Cadmium	Not Detected	0.98	100.0	227295	09/17/15	09/18/15	EPA 3052	EPA 6020
Chromium	19	1.7	100.0	227295	09/17/15	09/18/15	EPA 3052	EPA 6020
Copper	Not Detected	1.1	100.0	227295	09/17/15	09/18/15	EPA 3052	EPA 6020
Lead	Not Detected	1.6	100.0	227295	09/17/15	09/18/15	EPA 3052	EPA 6020
Mercury	0.035	0.020	1.000	227420	09/22/15	09/22/15	METHOD (described above)	EPA 7471A
Nickel	8.5	1.7	100.0	227295	09/17/15	09/18/15	EPA 3052	EPA 6020
Selenium	Not Detected	1.60	100.0	227295	09/17/15	09/21/15	EPA 3052	EPA 6020
Silver	Not Detected	0.98	100.0	227295	09/17/15	09/18/15	EPA 3052	EPA 6020
Thallium	Not Detected	1.2	100.0	227295	09/17/15	09/18/15	EPA 3052	EPA 6020
Zinc	Not Detected	7.8	100.0	227295	09/17/15	09/18/15	EPA 3052	EPA 6020

[*] Exposure to selenium in addition to arsenic could theoretically mitigate the harmful effects of arsenic because they are antagonistic toxicants, reducing the adverse effects of one another.[3] However, the presence of selenium in the results we obtained from our inductively coupled plasma mass spectroscopy tests was an analytical error. Selenium should not have been detected in the blank sample, and was recorded in the blank and the sample at the same concentration.

Table S2 contains the chemical analysis reported of the composition of lignite coal as reported by KEK (Korporata Energjetike e Kosovës), the coal mining company and power plant operator in Kosovo.

Table S2. Chemical Analysis of the Composition of Lignite Coal from KEK (Korporata Energjetike e Kosovës).

Coal Content Tested	**Quantity**	**Units**
Moisture	38-47	%
Dust	10-14	%
CO_x left over	27-30	%
C-fixed	17-20	%
Volatile matter	25-30	%
Burned matter	40-50	%
Calorific value	7942-9361	kJ/kg
	1700-2239	Kcal/kg
Total sulfur	1-1.1	%
Sulfur in dust	0.5-0.9	%
Sulfur burned	0.06-0.51	%

Table S3 contains the results of ICP-MS trace metal analysis for lignite coal in Kosovo compared to (1) average concentrations of trace metals in a cross section of lignite coal globally (IEA), and (2) trace metal concentrations reported in the literature for lignite coal in the US and China.[4,5,6]

Table S3. ICP-MS trace metal content in Kosovo lignite compared to lignite from other regions.

All values are in mg metal/kg coal.

Heavy Metal	Content in Kosovo Lignite Coal	International Energy Agency Global Average	Content in coals from China[5,6]		Content in coals from USA[4]		Content in coals around the world[4]
			Bai et al. (2007)	Dai et al. (2012)	Arithmetic mean	Geometric mean	
Arsenic	9.6 ± 1.6	2.69	4.09	3.79	24	6.5	8.3
Chromium	19 ± 1.7	17.6	16.94	15.4	15	10	16
Mercury	0.035 ± 0.020	0.091	0.154	0.163	0.17	0.10	0.10
Nickel	8.5 ± 1.7	11.1	14.44	13.7	14	9	13

When all units operate, KEK (Korporata Energjetike e Kosovës) manages approximately 30,000 tons of coal per day. According to KEK, the calorific value of lignite in Kosovo ranges from 7942-9361 kJ/kg. The full chemical analysis of lignite from KEK appears in Table S2.

Estimation of trace metal "emissions factor"

Model parameters:

Equation S1:

$$\frac{[\mathrm{TM}]}{\mathrm{kWhe}} = \frac{[\mathrm{TM}] * n_t * n_d * (\text{heat rate}) * \mathrm{C}_g}{\mathrm{Q}}$$

$\frac{[\mathrm{TM}]}{\mathrm{kWhe}}$ =Trace metal concentration normalized per kWh final electricity delivered (mg/kWh$_e$)

Trace metal concentration = [TM]

Thermal efficiency and heat rate (Btu/kWh)

Q = Calorific value of coal [kJ/kg]

Transmission and distribution network efficiencies = n_t *and* n_d (%)

Equation S2:

$$M_c = C_c F_c = C_s F_s + C_a F_a + C_g F_g$$

Equation (S2) shows trace metal mass balance. Our model focuses on trace metals in flue gas. The following parameters affect the trace metal portioning in coal.

M_c = mass of coal
C_c = concentration in coal
C_s = concentration in bottom ash
C_a = concentration in fly ash
C_g = concentration in flue gas

F_c = flow rate in coal
F_s = flow rate in bottom ash
F_a = flow rate in fly ash
F_g = flow rate in flue gas

Results:

Trace metal emission results per final kWh of electricity delivered

Table S4. Trace metal emissions expressed per final kWh of electricity delivered by country.

Trace metal emissions per final unit of electricity delivered [mg/kWh]	Kosovo	Kosovo efficient	China	IEA
[As]	22.3	9.3	6.6	1.1
[Cr]	44.1	18.4	26.9	7.1
[Ni]	19.7	8.2	24.0	4.5
[Hg]	0.08	0.030	0.29	0.03

Table S4 presents the data on metals concentration in mg/kWh_e.

Energy systems model

Our analysis uses four scenarios based on Kittner et al. (2016) for comparison to evaluate premature deaths. The four scenarios are presented below in Figures S2-5. Each scenario details the annual electricity generation supply mix until 2030. They include the business-as-usual generation mix, Euro 2030 path, low-cost solar with natural gas, and low-cost solar without natural gas. The detailed annual kWh generation for each scenario, which has been vetted through stakeholder engagement with civil society and policymakers, are based on the modeling work in Kittner et al. 2016.[7]

Kosovo C is the name of the proposed new coal-fired power plant. In our analysis we assume new coal plants will use best available pollution control technologies. TPP A and B represent the existing Kosovo A and B stations that currently comprise 98% of Kosovo's electricity generation. Zhur is a proposed pumped hydro storage plant included in the Kittner et al. (2016) analysis.

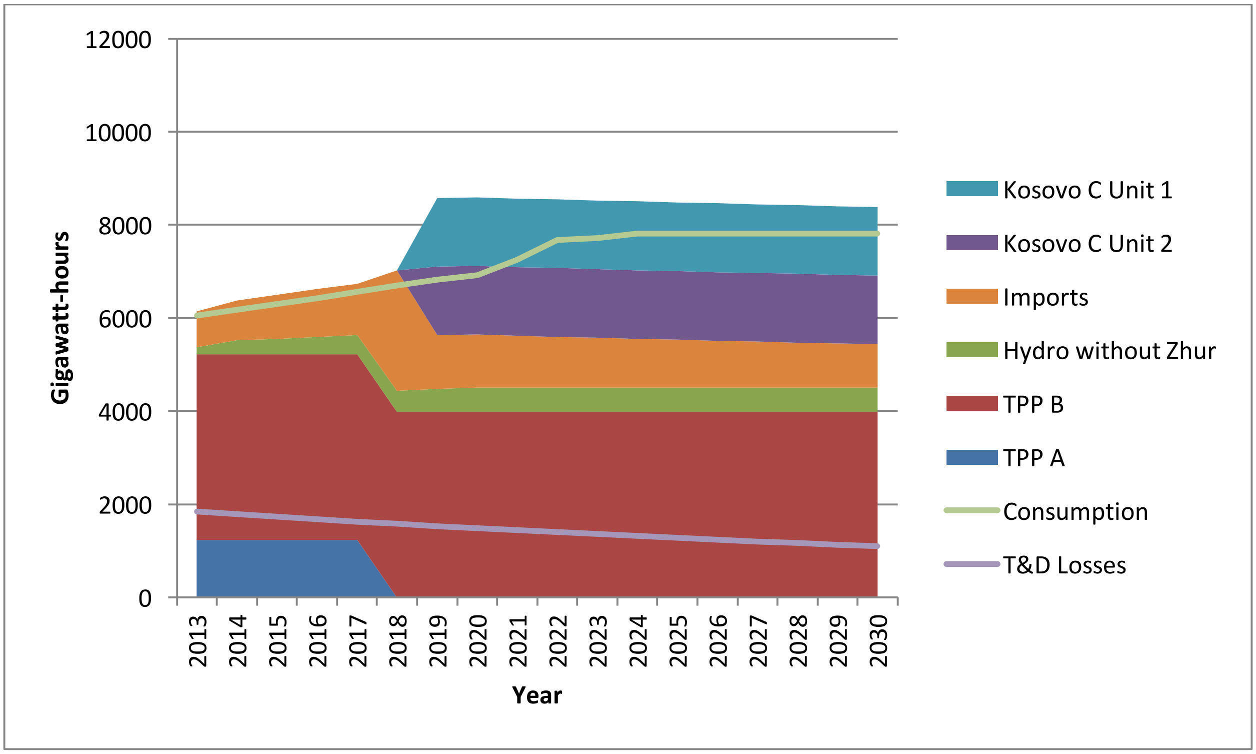


Figure S2. Projected sources of energy generation in a business as usual path that includes the development of Kosovo C.

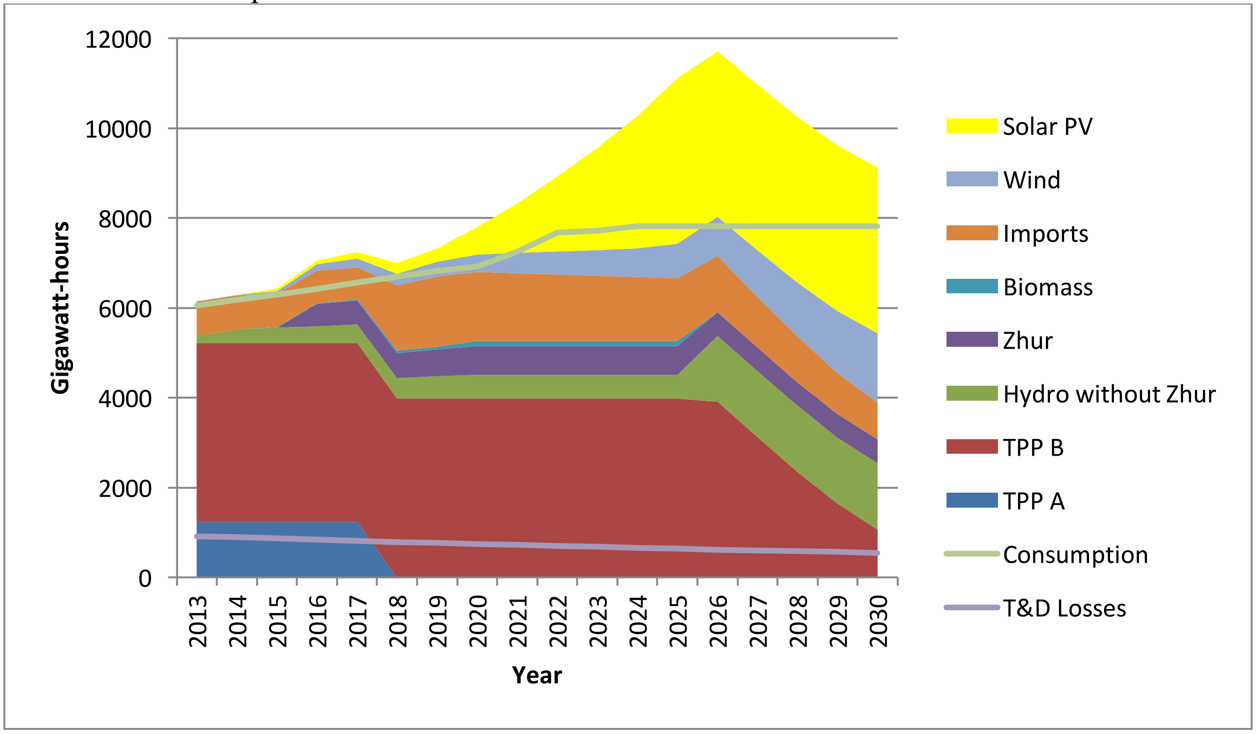


Figure S3. Projected sources of electricity generation in a Euro 2030 path met with energy efficiency measures, 27% CO_2 emission reduction, >27% renewable consumption, expanded power exchange for imports.

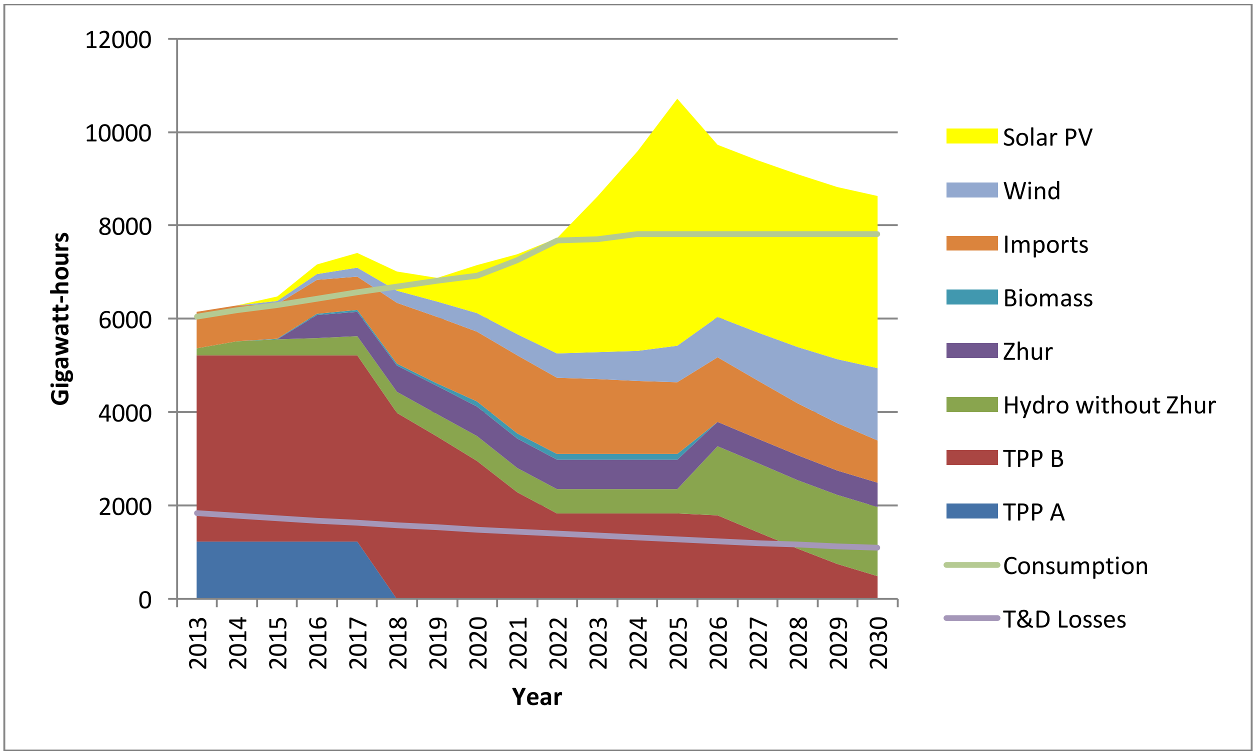


Figure S4. Projected sources of electricity generation in a low-cost solar pathway without flexible natural gas.

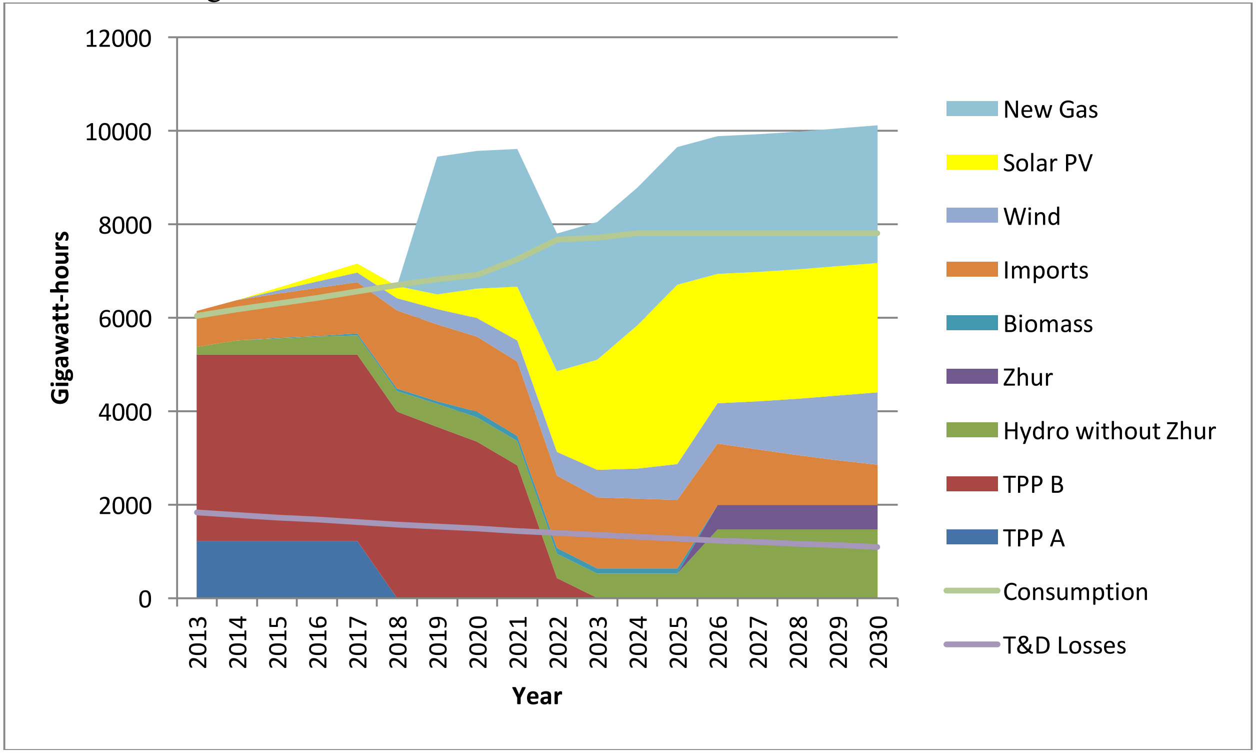


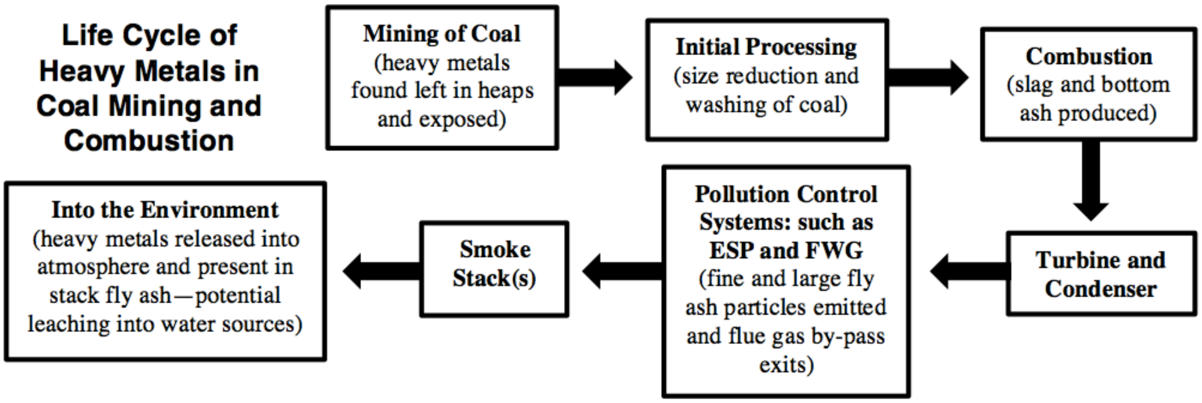
Figure S5. Projected sources of electricity generation in a low-cost solar pathway with flexible natural gas.

Table S5.

Table S5. Annual emissions documented from Kosovo A and B power stations. Source: Ref. (8).

	Annual emissions	**European Commission limit**
CO_2	5.7 million tons	
SO_x	733 ug/m^3	400 ug/m^3
NO_x	734 ug/m^3	500 ug/m^3
Dust & PM (2010)	**1,432 ug/m^3**	**50 ug/m^3**

Figure S6. Materials flow of heavy metals in coal from mining through combustion.



Exposure to pollutants from lignite coal differs across the life cycle of coal detailed in Figure S6, beginning with mining, through its processing and combustion, and finally with the disposal of fly ash waste. Although exposures could disproportionately affect workers in mining, transportation, and plant operation, their relatively small numbers led us to focus this particular analysis on impacts of coal combustion for surrounding communities.

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Chapter 3: Energy storage deployment and innovation for the clean energy transition

The clean energy transition requires a co-evolution of innovation, investment, and deployment strategies for emerging energy storage technologies. A deeply decarbonized energy system research platform needs materials science advances in battery technology to overcome the intermittency challenges of wind and solar electricity. Simultaneously, policies designed to build market growth and innovation in battery storage may complement cost reductions across a suite of clean energy technologies. Further integration of R&D and deployment of new storage technologies paves a clear route toward cost-effective low-carbon electricity. Here we analyze deployment and innovation using a two-factor model that integrates the value of investment in materials innovation and technology deployment over time from an empirical dataset covering battery storage technology. Complementary advances in battery storage are of utmost importance to decarbonization alongside improvements in renewable electricity sources. We find and chart a viable path to dispatchable $1/W solar with $100/kWh battery storage that enables combinations of solar, wind, and storage to compete directly with fossil-based electricity options.

In the face of the Paris climate agreement[1], a combined transition to clean energy and acceleration of decarbonization goals will require the refocusing of U.S. and international research and deployment schemes to promote energy R&D[2-4]. Dramatic cost declines in solar and wind technologies, and now energy storage, open the door to a reconceptualization of the roles of research and deployment of electricity production, transmission, and consumption that enable a clean energy transition[5,6]. While basic research remains a vital element to address a clean energy transition, increasingly an interdisciplinary approach is needed. Deeper integration with policies that build market growth[7] and cutting-edge business models will enable far faster uptake of critical research program outputs.

The majority of technological learning studies to date attribute deployment and innovation as isolated policies to expand and plan for future cost reductions[8-10]. However, we also know there are synergies between deployment and innovation where we can capitalize and strategically target public spending to benefit society[11]. This evolution has been demonstrated for clean energy technologies by analyzing s-curve trajectories and identifying missed opportunities for increased investment in wind and geothermal power R&D[12]. Previous frameworks investigated the interaction of technology-push and demand-pull policies to guide public programs that support clean energy through solar and wind deployment (learning-by-doing)[13-15]. The two-factor approach, established previously for wind turbines and solar photovoltaics[6,16], demonstrates a theoretical framework to apply to clean energy technologies to develop price trajectories and build technological roadmaps for dramatic energy transitions.

In this article, we develop a two-factor learning curve model to analyze the impact of innovation and deployment policies on the cost of energy storage technologies. We use patent activity, production output capacity (kWh), and historical global average prices to track learning rates of battery energy storage technologies. This allows us to investigate whether lithium-ion batteries can achieve necessary cost targets to push intermittent renewable systems with storage past conventional fossil fuel based generators. We also track U.S. and global R&D spending on the energy sector and derive implications for policymakers. With increased investment and strategic research, development, and deployment initiatives, the cost reductions of lithium-ion batteries enable cost competitive and dispatchable renewable PV and wind systems. Using an empirical global dataset of lithium-ion patent activity, production volumes, and average prices from 1991-2015, we find that innovation has a significant impact on prices of high-tech energy products and services, especially energy storage. This finding is in accordance with recent research on photovoltaics[6] and on wind turbines[16]. Therefore, we estimate two-factor models with a high prediction capability as an advanced conceptual approach and argue for further application in research compared to traditional one-factor learning curves.

Applying a framework to innovation in battery storage

Learning rates typically relate the cost reduction of new technologies to key factors like cumulative installed capacity or units of output produced and are widely employed to predict future trends[9]. Traditional one-factor models explain the decreased cost with increases in production volume (economies of scale, experience curve approach) only. Though the conventional one-factor model for innovation retains a good explanation value (adj. $R^2 = 0.9861$), the last four years of data overestimate the prices. Figure 1 shows the conventional one-factor learning rates of 17.31% for economies of scale and 15.47% using the experience curve approach. We explore three one-factor models representing annual production, cumulative production, and patent activity as a proxy for innovation.

The one-factor models under consideration here are as follows:

$$(1)\ P_t = \delta_0 + \delta_1 Q_t + \epsilon_t$$

$$(2)\ P_t = \zeta_0 + \zeta_1 CQ_t + \epsilon_t$$

$$(3)\ P_t = \vartheta_0 + \vartheta_1 I_t + \epsilon_t$$

where, P_t is the logarithmized price ($/kWh) (adjusted to 2015 US Dollars), Q_t is the logarithmized production volumes (MWh), CQ_t is the logarithmized cumulative production volumes until year t (MWh), and I_t is the innovation activity (cumulative patents until year t). The δ, ζ, and ϑ represent coefficients and ϵ_t represents the error term.

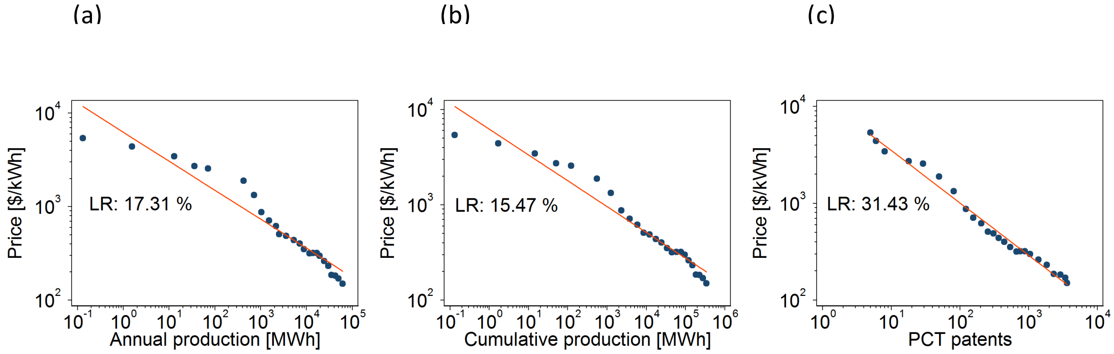

Figure 1: Learning rates using the traditional one-factor learning curve model for lithium ion battery storage. A shows the learning rate of economies of scale at 17.31 %. B displays experience curve approach with a learning rate of 15.47% for cumulative production. Learning rates for cumulative patents can be found in C and amount to 31.43%. Prices are adjusted to 2015 US-dollars. PCT is Patent Cooperation Treaty, an international patent treaty to protect inventions across nations.

Modeling economies of scale and innovation

In comparison, our two-factor learning curve model incorporates logarithmized production volumes (Q_i), and innovation activity (I_i) represented by cumulative international Patent Cooperation Treaty (PCT) patents during each year with P_i (logarithmized price) as the dependent variable. As both independent variables increased during our time series, statistics show a correlation of 0.9644, which introduces multicollinearity[20,21]. Information on the correlation and the variance inflation factor, analyzing the degree of multicollinearity can be found in Supplementary Tables 4-7. To resolve this issue, a two-step regression approach using a residual variable (η_i), as proposed by Qiu and Anadon, as well as Zheng and Kammen, was implemented[6,16]. Detailed information on the regression procedure is shown in the methods.

The final two-factor model (equation 4) is as follows:

$$(4)\ P_i = \gamma_0 + \gamma_1 Q_i + \gamma_2 I_i + \epsilon_i$$

$$(5)\ \mathit{Forecasted\ price} = \left(\frac{10^{\gamma_0}}{Q_i^{-\gamma_1}}\right)\left(10^{\gamma_2}\right)^{I_i}$$

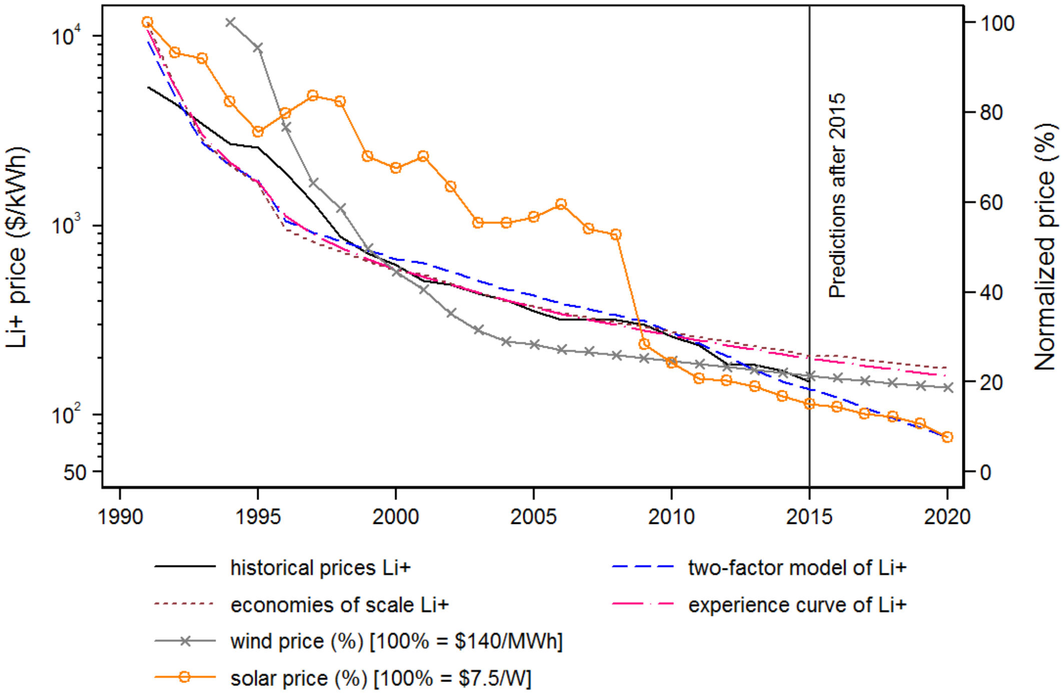

Figure 2: Comparing traditional one-factor models and the two-factor model to historical prices. Lithium-ion (Li+) forecasts are based on projects for production output, and patent activity on the average of the past five years. Prices for wind display averages of data from Qiu & Anadon until 2007[16]. From 2008 to 2019, prices are interpolated using the 2020 forecast[17]. Prices for solar are taken from Zheng & Kammen and extrapolated using their two-factor model forecast for 2014 and 2015[6]. Price reductions for wind and solar are normalized in percent (%) terms and should be read in the right-hand axis. All prices are adjusted to 2015 US-dollars.

The two-factor learning curve model (Fig. 2, eqn. 4) shows a learning rate of 16.9% for economies of scale (doubling annual production) and a decrease in prices of 2.0% per 100

PCT patents. Notably, the two-factor model explains the recent plunge of battery prices better than both conventional models using economies-of-scale or a classic experience curve approach. As Figure 2 shows, the two-factor model captures the past five years quite well (with $p<0.001$, adj. $R^2=0.9465$), while economies-of-scale and the experience curve approach systematically overestimate prices. The learning rates for lithium-ion batteries fall quicker than literature shows for c-Si PV modules (15.2%) and wind turbines (4.1-4.3%)[6,16]. We note that multi-factor models may achieve greater statistical significance (see Supplementary Note 1). To address omitted variable bias, we investigate a "four-factor" model (Supplementary Table 3), which incorporates raw material prices. We find that it does not maintain a p-value at the same level of significance as one- or two-factor models. In contrast, though one-factor models describe the price declines at a similar level of statistical significance, they overestimate prices during the 2010-2015 period and perform worse in terms of forecast error.

The two-factor model attributes part of the cost reduction to innovation, which is considered an important component for technological learning. Although costs are highly correlated with the production volume, according to the International Energy Agency (IEA) the share of responsibility of production volume and technological advancements on the cost reductions remain unclear[18]. Our framework supports prevailing technological learning literature that describes innovation as a more critical component of cost reductions compared to deployment[9]. For instance, if scientists increase battery energy densities by 20% through extensive R&D in material science, yet continue to use materials and production lines at their current cost, the price per kWh of storage could drop by 16.7% before increasing any production volumes. This is also exhibited through advances in net energy performance (characteristics including cycle life and energy capacity) measured by energy stored on energy invested[19].

Forecasting future storage prices

Applying the two-factor model to recent production forecasts of leading industry experts[48] and assuming that patent activity stays on the high level of the five-year average (2011-2015), provides optimistic results with consumer cell prices falling below $100/kWh by 2018. Figure 2 and Table 1 highlight their respective price trajectories. The forecast is based on 25 annual observations, and though the sample is small, it represents the best available information in a nascent market. We include a detailed sensitivity matrix in Supplementary Note 2 varying future patent activity and production levels since patent counts historically follow random Poisson processes[22]. We incorporate the effect of time lags on patents and knowledge stock depreciation, where patents in the past have less effect on prices than recent patents (Supplementary Note 3). We find lower cost reductions than existing forecasts in the literature, which in the past has found a systematic underestimation of falling electric vehicle battery costs[23]. We account for raw material prices in a "four-factor" model controlling for the impact of raw lithium and cobalt prices, which we find to lower the learning rate slightly (14.82%), and attributes greater reductions to innovation rather than deployment. However, raw material prices may not be as critical to battery cost reductions as the experience of wind generation to steel prices. Diverse material components comprise lithium-ion batteries, though lithium and cobalt represent important parts of the cathode[24]. Controlling for raw material prices in a "four-factor" model is not as statistically significant ($p<0.16$) as the two-factor model ($p<0.001$). However, sustainability criteria could guide future development as new material innovations become viable[25]. One potential bias in the two-factor model may be the exclusion of subsidies that are typically proprietary and difficult to track. Further research in this area would greatly address a gap in technology and policy innovation studies.

Tab 1: Forecasted prices by using two-factor learning curve model. Second column represents the forecasted values. Third and fourth column show estimations for EV/ES (electric vehicle/electric energy storage) cells (+24.85%) and for battery packs (+30.89%) respectively. Cells prices for electric vehicles and energy storage are higher due to different standards and chemistry. This model assumes the same learning across cells and battery packs. Prices are in 2015 US-$ and shown per kWh.

Year	Forecast: consumer cells	EV/ES cells	EV/ES battery pack
2016	124.15	155.00	202.88
2017	109.18	136.31	178.41
2018	96.38	120.33	157.50
2019	85.55	106.81	139.80
2020	76.03	94.92	124.24
sensitivity range	(66.17-88.32)	(82.61-110.27)	(108.13-144.33)

Advances in lithium-ion batteries will likely spur the adoption of EVs. Studies show that EVs will become cost-competitive to internal combustion engine vehicles with prices for battery packs reaching $125-165 per kWh assuming 2015 average U.S. gasoline prices[26,27]. According to our model, this critical threshold is reached in 2017 as an upper bound and by 2020 in the low case. Besides battery prices, gasoline prices, electricity rates, and yearly mileage significantly impact when EVs reach cost competitiveness. These forecasts are lower than previously reported literature values[23].

We also investigate the cost of learning-by-searching compared with the cost of deployment initiatives through the two-factor model results. Learning-by-searching represents the impact of research, development, and demonstration (RD&D) on the cost of an energy technology[16]. To estimate this, we scaled back patent activity by 33% from the current trajectory in the two-factor model and found an additional 307 GWh of global deployment is required through learning-by-doing alone to achieve a $100/kWh battery storage threshold by 2020 (Supplementary Note 2). For perspective, the Tesla Gigafactory plans to deploy 35 GWh per year. Patent activity critically drives the two-factor model. A lack of patent activity would drastically increase costs to reach cell level prices of $76/kWh. At the most extreme case of no new innovation, the opportunity cost of meeting cost reduction targets through deployment alone would be extremely high, in exceedance of $140 billion dollars through 2020. This is not likely or feasible, but highlights the importance of innovation to achieve cost reductions through the two-factor framework. The vast majority of recent solar PV and wind cost reductions, however, stem from process improvements and corporate R&D that use profits from deployment to further drive innovation[41]. If true for storage, this feedback between innovation and deployment limits our ability to completely decouple the effects of both R&D and deployment targets. This warrants further research and underscores the importance of developing both learning-by-searching and learning-by-doing policies, forming the development of a learning-by-researching and doing approach.

Further, energy storage at the utility and residential scale is on the verge of reaching grid and socket parity. We find that at current targets, if the U.S. reaches the “SunShot” target pricing for solar electricity at $1/W, the price trajectories estimated here would make residential solar and electric battery storage cost competitive with grid electricity by 2020, achieving an LCOE of around $0.11/kWh as detailed in the appendix. Currently, lithium-ion battery-based energy storage remains a niche market for protection against blackouts, but our analysis shows that this could change entirely, providing flexibility and reliability for future power systems. This finding contrasts with recent studies, postulating the value of energy storage for decarbonizing electricity to be low, given high costs of storage technologies[28,29]. According to our forecasts, both studies forecast pessimistic future prices for energy storage that do not consider the complementary effects of innovation and deployment and the value of flexibility for power and/or energy dense storage options in future power systems. Gigawatt-scale grid storage would improve the T&D system, resulting in lower future investments necessary to ensure grid stability and improve customer reliability[30]. Although total project costs, such as labor and balance-of-system components are included in the capital costs, the modeling highlights the close proximity of this target for lithium and non-lithium based electrochemical options.

Implications of R&D spending on price decreases

To enable a storage-driven transition, further research is necessary to maintain patent activity levels. Public R&D spending and private research projects directly trigger innovation by stimulating research and facilitating a high level of experimentation, yet US federal R&D spending continues to decline. Photovoltaic research remains a prime example of the ability for R&D programs to drive growth and cost reductions[31]. During the past decade, however, public R&D spending in energy did not keep pace with rising revenues of the energy sector. Figure 3 shows the U.S.-federal R&D expenditures between 1976 to 2015. During this period, total U.S. federal R&D spending plunged from 1.2% to 0.8% of the U.S. GDP[32,33]. Spending of energy R&D plunged from 0.3% to 0.013% respectively. Global share of energy to total R&D spending declined on average from over 10% to 3.9% as of 2013. The share of energy to total R&D amounted to 2.1% in the U.S. in 2015[32,33]. The current share of energy R&D spending does not reflect the importance of clean energy technology deployment and its role in meeting global climate objectives. With regard to battery technology, an urgent call for action to increase public R&D spending and therefore push innovation forward and prices for storage down becomes apparent to create cost-competitive dispatchable solar, wind, and storage electricity.

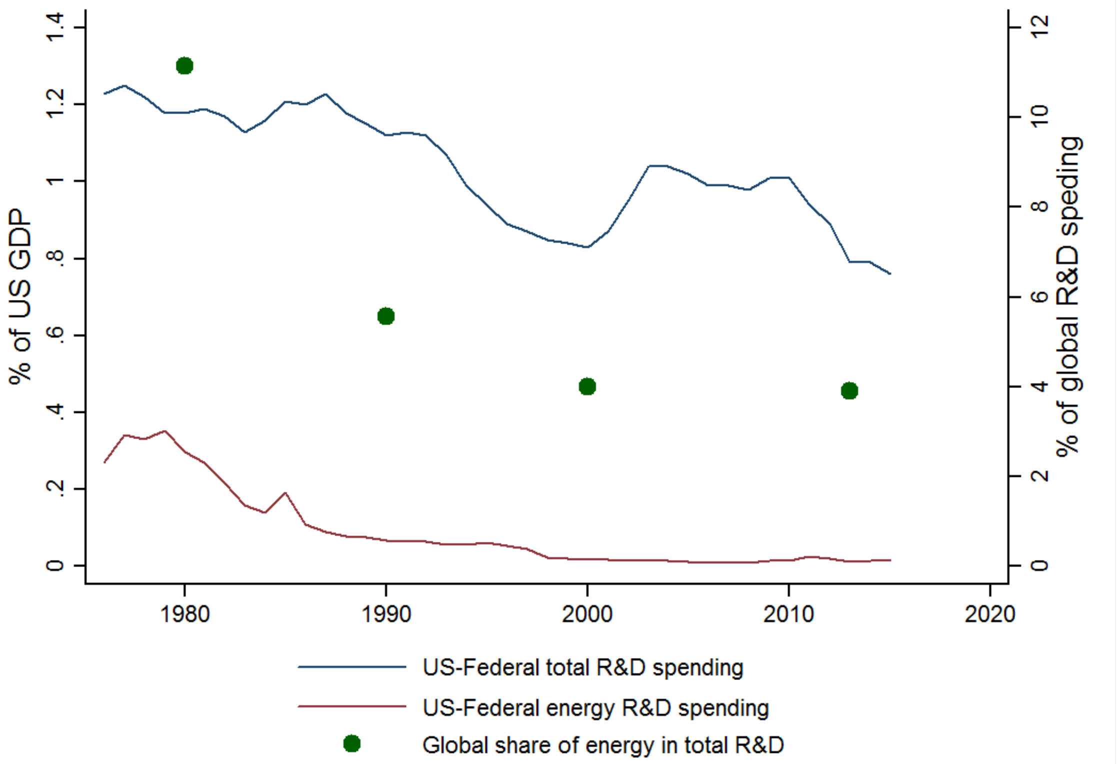

Figure 3: U.S.-federal R&D spending from 1976-2016. *U.S.-federal R&D spending declined over the past four decades from about 1.2% to 0.8% of the U.S. GDP. In the same timeframe, federal R&D spending of energy-related topics plunged from over 0.3% to 0.013%. The dark green dots show a similar development for the share of energy-related R&D to total R&D spending. In the late 70's, energy R&D accounted for over 10% of total R&D of which more than 50% was allocated to nuclear energy globally. By comparison, the international community allocated 3.9% of R&D funds to energy related activities in 2013. Data are from AAAS*[32,33].

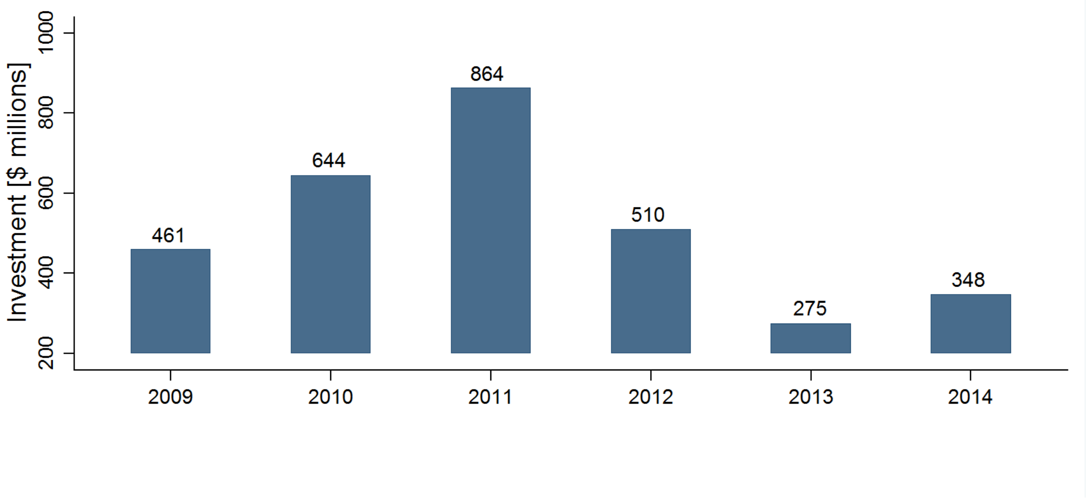

Figure 4: Global corporate and VC investment in the energy storage sector. *Following post-financial crisis years 2009, 2010 and 2011, investment levels dramatically decreased by 2014. Source: i3 (ref.* 34*).*

Further advances in material science may foster an increase in battery energy density, which remains crucial to increase the driving range of EVs to a competitive level with conventional vehicles and to reduce the cost of grid-scale storage applications. Current patent activity for lithium-ion batteries is on a high level, though has plateaued within the last five years. This model highlights the importance for policymakers to stabilize declining public R&D spending and fuel innovation activity through systematic funding of clean tech R&D projects to meet decarbonization goals in a cost-effective manner, affirming results from previous studies and extending to not just electricity generation sources, but storage[31]. Additionally, policymakers should initiate a standardized framework favoring private venture capital investing in clean technology. Venture capital is seen as vital to the clean-tech industry[35,36] and research indicates that VC investments are more effective than (public) R&D with regard to patenting, thus could be applied to target emerging electrochemical and mechanical storage systems[37]. Though large loan guarantees to VC-backed firms have lacked prior cost-effectiveness, government initiatives like the Small Business Innovation Research Program (SBIR), university R&D programs, and large-scale demonstration projects have seen more success[38].

Discussion

According to our two-factor model, adoption policies that incentivize total deployment of EVs or energy storage systems are expensive measures. We calculate that achieving a lower boundary of $125/kWh for EVs by 2018 at the current five-year patent average, would require a more than two-fold increase of yearly production output than currently forecasted. This equals a production of about 300 GWh of additional manufactured capacity. In particular, lithium batteries for consumer devices comprise a significant market share of total production, and it’s likely energy applications will continue to lag. Learning-by-searching, or innovation (learning by “*re*searching”), very likely plays a larger role than deployment incentives alone by achieving more rapid cost reductions in a shorter time frame. Adoption policies could yield cost improvements at the manufacturing or systems-level value chain for EVs and grid-scale storage. However, incentivizing deployment through capacity targets may create significant windfalls where customers receive incentives for what they would have bought regardless. Deployment targets for energy storage may not prove as effective as research-based, innovation-driven activities.

We propose a strategy that allocates funds toward more cost-effective research and development measures. Governments can play a critical role for promoting research advances and innovations that drive down cost further. Outlining future research and legal frameworks to enable distributed energy systems and vehicle-to-grid interactions is one emergent research area. Another research focus is to understand conditions when grid storage is valuable, operational frameworks to provide spinning reserves or ancillary services, demand-response, and opportunities for emission reductions. For vehicle storage applications, incentivizing and designing a tight-meshed charging infrastructure alleviates range limits. All of these outcomes could contribute to innovation-driven cost reductions through not only materials research, yet also deployment.

Developing research programs with an emphasis not only on electrochemical storage for material science advances, but also emerging mechanical storage applications would provide increased flexibility in power system planning. Some claim that mechanical storage applications could undercut electrochemical storage in terms of price, however, there may be a role for both. Long duration bulk storage capacity and short bursts from high power devices that can provide frequency regulation, ancillary services, or simply inject power to the grid during times of intermittency. Finding complementarity between increasing storage performance through energy density and lowering cost will be necessary for both vehicle and grid-scale applications. Storage technologies can learn from asset complementarity driving PV market growth and find niche applications across the clean tech ecosystem, not just for pure kWh of energy storage capacity[39]. It's likely that multi-utility storage applications may surface as a result of innovation and deployment-driven cost reductions.

Based on the two-factor model, we recommend policymakers to adopt balanced innovation and deployment policies. A portfolio of policies is more likely to successfully drive environmental change than a single policy[40]. We note that the relative decline in public R&D spending could forestall critical cost reduction and advances toward achieving a deep decarbonization in the electricity sector and bringing new material advances from the lab to the market. We find significant value associated with investing in increased patents through research, and one way to drive this research is through government spending that could achieve drastic cost reductions for energy storage systems. The diversity of materials for current lithium-based batteries suggest that unlike solar photovoltaics or wind turbines, it is likely new material advances in storage technologies are necessary to achieve a $100/kWh target.

Patent activity and R&D spending continue to drive down the price of electrochemical battery storage technologies. Our two-factor learning curve estimates a turning point in 2019 when forecasted prices cross the threshold of $100/kWh contradicting current forecasts and studies. The strong relationship in the two-factor learning curve suggests that U.S. R&D could enable further cost reductions through investment in developing new battery materials. Designing a deployment strategy would lower overall costs in decarbonizing the electricity grid and transportation sectors, which account for more than 60% of overall CO_2 emissions combined. Therefore, critical to evaluating new technologies remains the material choices to improve safety, energy density, and cost. New research promoting soft-side innovations and business models will expedite integration of electrochemical storage into common markets. Further government support is necessary to promote responsible R&D spending that enables serious cost reductions across solar, wind, and storage, while also decarbonizing electricity and transportation. The U.S. has the opportunity to become a leader, not a laggard, in electric battery storage manufacturing and development. We find that R&D spending is a strong indicator of driving innovation. Therefore, concomitant increases in R&D spending across energy research would promote a diverse suite of storage technologies and material science advances.

Methods:

Global battery price and output volume data collection:

We compiled a comprehensive global dataset of average prices and global production output of lithium-ion consumer cells from 1991 to 2015 available at http://rael.berkeley.edu/project/innovation-in-energy-storage. As data within this industry is typically proprietary and not accessible via a transparent platform, we cross-validated data with industry experts and leading international research agencies specializing in the battery market at the Energy Storage North America meeting in October 2015[49].

Collection of patent data as a proxy for innovation:

Previous research highlights three proxies to measure innovation: private and public R&D expenditures, literature-based innovation output, and number of patents[42].

We consider patents filed according to the Patent Cooperation Treaty (PCT) as a proxy for innovation. Following the work of Griliches[43], others evaluated patenting in the energy sector, and concluded that patents are a valid indicator to measure innovativeness within the energy sector[2,41]. This result has been extended and re-confirmed by a number of authors[44]. PCT patent reviews contain high quality standards and innovators seeking international protection file for PCT patents, attesting to the high economic value of their patent, which represents a gold standard for patent information[45].

Queries were conducted using Patentscope, a database of the World Intellectual Property Organization (WIPO), retrieving patent information by searching for the keywords "lithium and ion and (battery or batteries or accumulator or accumulators or cell or cells)" on the patents' front page. We include patents in the manufacturing process and were inclusive of any patent that contained the search terms we determined that we found in Patentscope. Supplementary Figure 1 highlights the patent activity over time for lithium-ion batteries.

Multivariable regression analysis to develop a two-factor learning curve model:

For our analysis, we use a two-factor learning curve model. Traditional one-factor models explain the decreased cost with increases in production volume (economies of scale, experience curve approach) only. However, the two-factor model attributes part of the cost reduction to innovation, which is considered an important component for technological learning. Although costs are highly correlated with the production volume, according to the International Energy Agency (IEA) the share of responsibility of production volume and technological advancements on the cost reductions remain unclear[18]. For instance, if scientists increase battery energy densities by 20% through extensive R&D in material science, yet continue to use materials and production lines at their current cost, the price per kWh of storage could drop by 16.7% before increasing any production volumes. This is an illustrative example demonstrated by the hypothetical situation where a $200/kWh battery increases in energy density by 20%, which would change the price per kWh to $167/kWh before changing anything in relation to the bill of materials.

Our two-factor model incorporates logarithmized production volumes (Q_i), and innovation activity (I_i) represented by cumulative PCT patents during each year with P_i (logarithmized price) as the dependent variable. To resolve the issue of multicollinearity, a two-step regression approach using a residual variable (η_i), as proposed by Qui and Anadon, as well as Zheng and Kammen, was implemented[6,16].

Developing the two-factor learning curve model follows the subsequent rationale:

(6) $I_i = \alpha_0 + \alpha_1 Q_i + \eta_i$

(7) $\eta_i = I_i - \alpha_0 - \alpha_1 Q_i$

After introducing the residual variable to remove the correlation, the reformed Eq. 7 is inserted in Eq. 6. Further transformation gives the new coefficients γ_0, γ_2 and γ_3. Information on the correlation and variance inflation factor after introducing the residual variable is displayed in Supplementary Tables 4-7.

(8) $P_i = \beta_0 + \beta_1 Q_i + \beta_2 \eta_i + \epsilon_i$

(7) in (8) $P_i = \beta_0 + \beta_1 Q_i + \beta_2 I_i - \beta_2 \alpha_0 - \beta_2 \alpha_1 Q_i + \epsilon_i$

(9) $P_i = [\beta_0 - \beta_2 \alpha_0] + [\beta_1 - \beta_2 \alpha_1] Q_i + \beta_2 I_i + \epsilon_i$

$$\gamma_0 = \beta_0 - \beta_2 \alpha_0$$

$$\gamma_1 = \beta_1 - \beta_2 \alpha_1$$

$$\gamma_2 = \beta_2$$

The final model and be found in Eq. 4 and 5.

(4) $P_i = \gamma_0 + \gamma_1 Q_i + \gamma_2 I_i + \epsilon_i$

(5) $Forecasted\ price = \left(\frac{10^{\gamma_0}}{Q_i^{-\gamma_1}}\right)(10^{\gamma_2})^{I_i}$

LCOE System Cost Calculation

We assume LCOE for residential PV in Germany: 10.7–15.6 \$-cent + LCOE Powerwall ~15 \$-cent < 36.3 \$-cent average residential electricity rate in Germany when considering it at "socket parity." This is a term referring to the state when cost is equivalent to the retail rate of electricity[46].

We calculate system LCOE costs if SunShot solar goal is achieved by 2020, where LCOE for PV reaches \$0.05/kWh by 2020[47]. We assume a 2-kW residential home solar system represented by average US insolation levels at ~4.8 kWh/m^2/day that could be installed in Kansas City, MO (used by NREL to represent average US insolation). We also assume Tesla's lithium-ion based Powerwall is \$350/kWh for residential customers and \$250/kWh at utility-scale and reaches \$100/kWh by 2020. We use a 7 kWp Powerwall with 13.5 kWh energy capacity ratings that charge for six hours during the day with 90% roundtrip efficiency and 100% depth of discharge. The battery discharges at night when electricity is more expensive and net load is higher. This would place residential solar+storage at an estimated \$0.11-0.12/kWh target. Based on a ten-year project lifetime, and in the optimal case assuming a full charge-discharge cycle on a daily basis ignoring losses, LCOE at current prices is \$0.15/kWh at residential scale and \$0.10/kWh at utility scale. Based on current price trajectories and a patent activity level of 444 patents per year using our model, battery prices will fall from 2016 to 2020 by 39%, which puts utility-scale battery storage roughly equivalent to \$0.06/kWh based on current usage rates that model integration of storage into power grids with high penetrations of renewables[5]. Then we find that though distributed PV and battery storage may not be competitive everywhere by 2020, systems will already hit grid parity in certain locations where electricity prices are higher than average coupled with high solar irradiation. This also occurs before including other use-cases including peak-shaving, ancillary services, voltage regulation, and the displacement of natural gas peaker plants. In Hawaii and many other states, PV and storage will achieve grid parity[46,48]. This could be achieved at a solar+storage target of \$0.11-0.12/kWh.

Data Availability:

The data that support the plots within this paper and other findings of this study are publicly available on the Innovation in Energy Storage database at http://rael.berkeley.edu/project/innovation-in-energy-storage/ and in the Supplementary Information.

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Author contributions:

NK conceived and NK and FL designed the study. NK, FL, and DMK collected data. NK and FL analyzed data and wrote the paper. FL ran the statistical test. DMK supervised the research, guided the study, and edited the paper.

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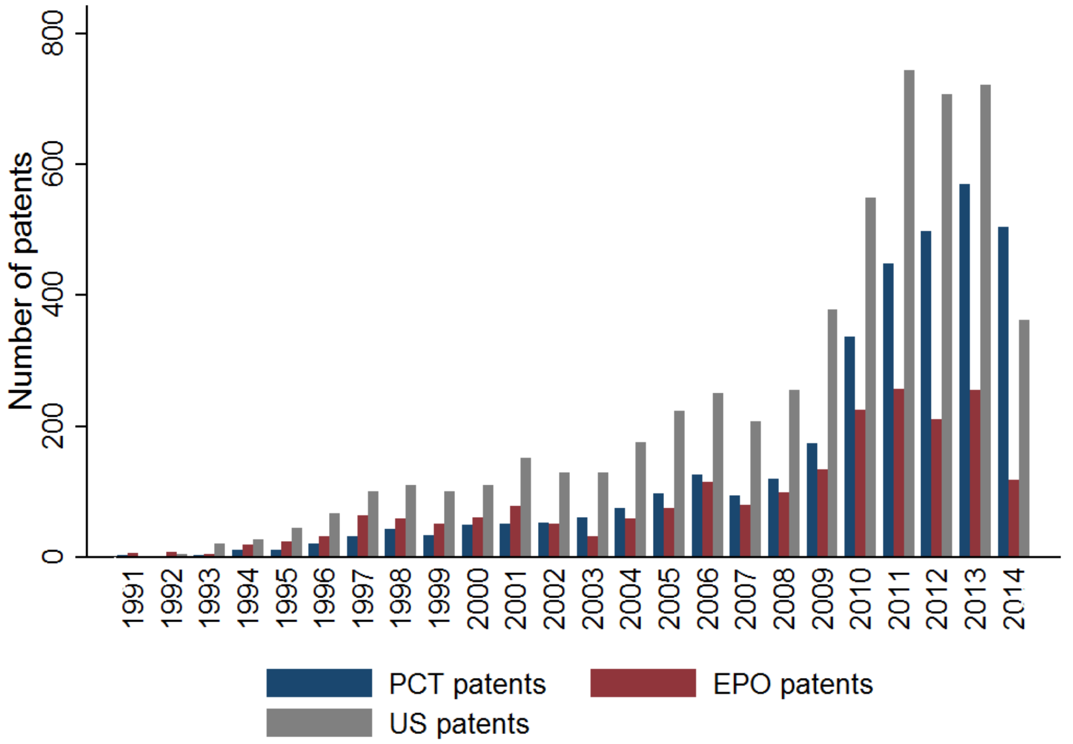
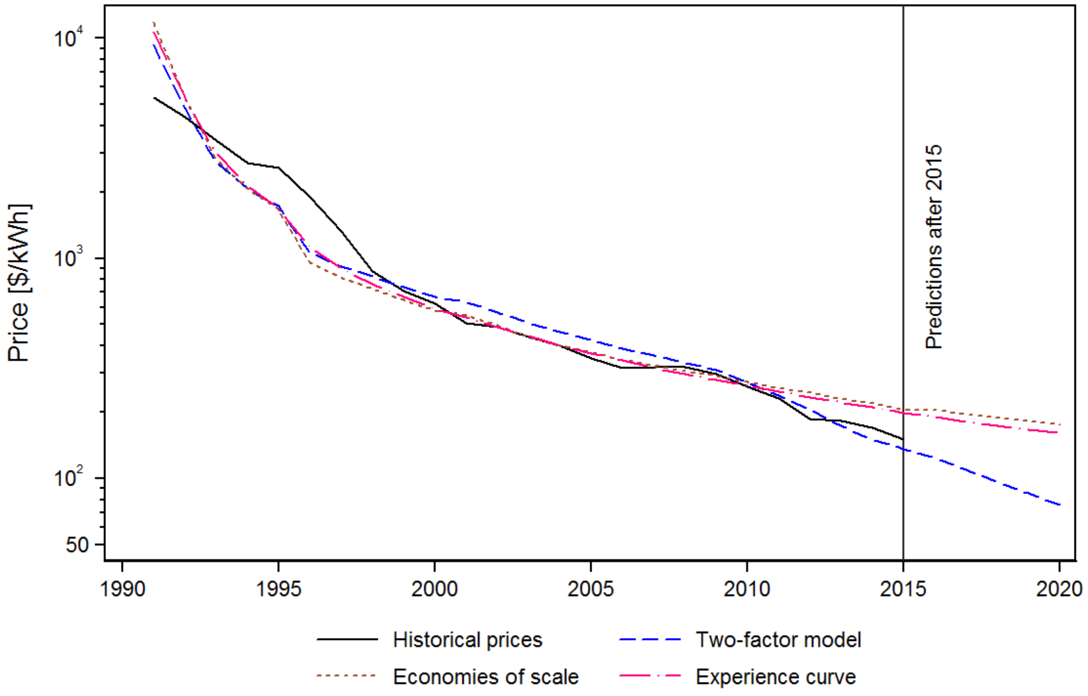
Supplementary Information:



Supplementary Figure 1: Development of patents registered at the U.S., European patent office, and Patent Cooperation Treaty for lithium-ion battery technologies. *Queries were conducted using the Patentscope database, part of the World Intellectual Property Organization (WIPO). We searched for terms including "lithium and ion and (battery or batteries or accumulator or accumulators or cell or cells)" on the patents' front page. We include patents in the manufacturing process and were inclusive of any patent that contained the search terms we determined that we found in Patentscope. The last five years show that patent activity in terms of patents being filed and approved slowed down. In particular, EPO and PCT patents show that a plateau has been reached. Data for 2014 may still be subject to a change in patent count, as not all filed patents have been granted yet. Search queries at patent databases were conducted in early 2016.*



Supplementary Figure 2: The falling cost of lithium-ion battery storage by comparing historical prices with one- and two-factor models that incorporate economies of scale and experience. *The two-factor model investigates innovation and deployment, taking into account learning-by-searching and learning-by-doing.*

Results of one- and two-factor models

	Equation 1	Equation 2
Coef 0	α_0 =-711.5858*** (430.2888) 0.000	β_0 = 3.797658*** (0.0542746) 0.000
Coef 1	α_1 = 480.6329 (120.6356) 0.112	β_1 = -0.3101608** (0.0152164) 0.003
Coef 2		β_2 = -0.0000881*** (0.0000263) 0.000
# obs	25	25
F	15.87	213.18
Prob > F	0.0006***	0.0000***
R^2	0.4083	0.9509
Adj. R^2	0.3826	0.9465

*Supplementary Table 2: Overview of key regression results for Eq. 1 and Eq. 2. Standard error of coefficients is displayed in parentheses. The p-value follows the convention: *** <0.001< ** <0.01< * <0.05 and are stated below the standard error. Low R² for Eq. 1 is desired as the regression is used for introducing the residual variable. In order to validate the procedure and the final model (based on data from 1991 to 2015), a pre-model (based on data from 1991 – 2006) was developed. After excluding the first two years of the time series due to being outliers, the test model was used to calculate prices from 2007 to 2015. The two-factor pre-model successfully forecasted the drastic decline in prices within the last years. Forecasted prices show a mean deviation of 23.43%, which can be seen as a very satisfactory result, since forecasts by industry analysts showed a significant higher level of deviation for these years. Forecasts and their deviation to the real values are shown in Supplementary Table 8.*

	one-factor models			two-factor model
	A	B	C	Eq. 2 (leading to D)
Coef 0	-3.797221*** (0.0651777) 0.000	3.79099*** (0.0531146) 0.000	4.085781*** (0.0334454) 0.000	3.797658*** (0.0542746) 0.000
Coef 1	-0.3100554*** (0.0182732) 0.000	-0.270016*** (0.0130085) 0.000	-0.5407248*** (0.0131083) 0.000	-0.3101608** (0.0152164) 0.003
Coef 2				-0.0000881*** (0.0000263) 0.000
# obs	25	25	25	25
F	287.91	430.85.18	1701.61	213.18
Prob > F	0.0000***	0.0000***	0.0000***	0.0000***
R^2	0.9260	0.9493	0.9867	0.9509
Adj. R^2	0.9228	0.9471	0.9861	0.9465
BIC	-26.17094	-35.62775	-69.0026	-33.21648

*Supplementary Table 2: General overview of statistical results for all four models. Standard error of coefficients is displayed in parentheses. Higher BIC scores either indicate a worse fitting of the models, a model using more parameters or both. The p-value follows the convention: *** <0.001< ** <0.01< * <0.05 and are stated below the standard error.*

	one-factor models			two-factor model	four-factor model
	A	B	C	Eq. 2 (leading to D)	Eq. 5
Coef 0	-3.797221*** (0.0651777) 0.000	3.79099*** (0.0531146) 0.000	4.085781*** (0.0334454) 0.000	3.797658*** (0.0542746) 0.000	1.1723533* (0.6300552) 0.014
Coef 1	-0.3100554*** (0.0182732) 0.000	-0.270016*** (0.0130085) 0.000	-0.5407248*** (0.0131083) 0.000	-0.3101608*** (0.0152164) 0.003	-0.2875361*** (0.0162777) 0.000
Coef 2				-0.0000881*** (0.0000263) 0.000	-0.0001167*** (0.000038) 0.007
Coef 3					0.2129343 (0.146463) 0.163
Coef 4					0.2606368 (0.1684335) 0.139
# obs	25	25	25	25	23
F	287.91	430.85.18	1701.61	213.18	137.14
Prob > F	0.0000***	0.0000***	0.0000***	0.0000***	0.0000***
R^2	0.9260	0.9493	0.9867	0.9509	0.9682
Adj. R^2	0.9228	0.9471	0.9861	0.9465	0.9612
BIC	-26.17094	-35.62775	-69.0026	-33.21648	-35.22165

*Supplementary Table 3: General overview of statistical results for all four models. Standard error of coefficients is displayed in parentheses. Higher BIC scores either indicate a worse fitting of the models, a model using more parameters or both. The p-value follows the convention: *** <0.001< ** <0.01< * <0.05.*

The four-factor model appears in eqn. 5.

$$(5)\quad P_i = \delta_0 + \delta_1 Q_i + \delta_2 \eta_i + \delta_3 PLi + \delta_4 PCo + \epsilon_i$$

PLi = logarithmized price of Lithium ($/kWh) adjusted to 2015 USD
PCo = logarithmized price of Cobalt ($/kWh) adjusted to 2015 USD

	logy_aprice (P_t)	logy_output (Q_t)	cum_pctpatents (I_t)
logy_aprice (P_t)	1.0000		
logy_output (Q_t)	-0.9623	1.0000	
cum_pctpatents (I_t)	-0.9933	0.9644	1.0000

Supplementary Table 4: Correlation matrix of the main regression variables. The matrix shows a high correlation between output volume and patent activity, which is a first indication of multicollinearity.

	VIF	1/VIF
logy_output (Q_t)	14.30	0.069917
cum_pctpatents (I_t)	14.30	0.069917
Mean	14.30	0.069917

Supplementary Table 5: Analysis of the variance inflation factor. The calculation of the variance inflation factor revealed the presence of multicollinearity. Multicollinearity is considered a problem for variables with VIF values over ten.

	logy_aprice (P_t)	logy_output (Q_t)	residual variable (n_t)
logy_aprice (P_t)	1.0000		
logy_output (Q_t)	-0.9623	1.0000	
residual variable (n_t)	-0.1558	-0.0021	1.0000

Supplementary Table 6: Correlation matrix after incorporation of the residual variable. The matrix shows a very low correlation between Q_t and the residual variable n_t.

	VIF	1/VIF
logy_output (Q_t)	1.00	0.999996
residual variable (n_t)	1.00	0.999996
Mean	1.00	0.999996

Supplementary Table 7: Analysis of the VIF after incorporation of the residual variable. After introducing the residual variable, the variance inflation factor shows the absence of multicollinearity.

Year	**Average price [$]**	**Forecasted price [$]**	**Deviation**
2007	320.1	245.3	|-23.0%|
2008	319.3	396.9	24.3%
2009	298.3	363.0	21.7%
2010	260.9	294.7	13.0%
2011	231.8	251.7	8.6%
2012	185.8	229.8	23.7%
2013	183.1	203.0	10.9%
2014	170.2	204.7	20.3%
2015	150.0	248.2	65.4%
Mean			23.4%

Supplementary Table 8: Pre-Model forecasts & deviation:

Coefficient	**Value**
γ_0	3.73496729
γ_1	-0.26781704
γ_2	-0.0000881

Supplementary Table 9: Values for the coefficients of the real model

	Mean	Standard deviation	Minimum	Maximum
y_aprice	1142.466	1446.228	150	5394.66
logy_aprice (P_t)	2.7852	0.4729792	2.18	3.73
y_output	13514.85	17534.07	0.1	61487
logy_output (Q_t)	3.264	1.467958	-0.9	4.8
cum_output	67087.28	96196.25	0.1	337871.1
logcum_output	3.724926	1.706709	-0.8860567	5.528751
y_pctpatents	144.28	178.1686	1	570
logy_pctpatents	1.73479	0.757657	0	2.755875
cum_ pctpatents (I_t)	857.2	1104.121	5	3610
logcum_ pctpatents	2.405254	0.8688611	0.69897	3.557507
residual variable (η_t)	1.052853	847.7372	-709.7451	2019.939

Supplementary Table 10: Summary of key statistics for regression variables.

Supplementary Note 1: Omitted Variable Bias

In our two-factor model, the two key independent variables measure deployment (production volume) and innovation (patent count). We use ordinary least squares (OLS) regression to estimate the impacts of deployment and innovation. One key assumption is that we did not exclude factors that could influence price in the error term. To test our assumptions, we account for omitted variable bias by investigating the correlation between raw lithium and cobalt prices on prices since they are two main materials required for the majority of lithium batteries and have previously had impacts on electric vehicle battery costs[1]. These materials also comprise a significant share of the raw material costs (estimated at 60% of total battery costs)[2]. Though the lithium price has fallen in absolute terms since the 1990's, the price trend since 2005 is increasing due to scarcity and mining costs. Supplementary Tables 11 and 12 detail the correlation matrix and key regression results for raw lithium and cobalt prices and lithium-ion batteries. We find low explanatory value, suggesting our assumption to rely on patent count and production volume is reasonable.

Also our data represent price instead of cost. We believe this is a reasonable assumption in this case. Though there could be various non-technological factors that influence price including market structure or industry competition, at the moment, for nascent storage technologies the current market exhibits a high level of competitiveness in its early stages. This means costs are more representative within prices. This may be a limitation, but the data do not yet exist for full value chain costs of energy storage systems. Secondly, with regard to subsidies that could influence price, many battery manufacturers are subsidiaries of larger corporations (including LG, Samsung, and Panasonic). These companies can cross subsidies across subsidiaries due to strategic reasons, which is one caveat in our results as battery manufacturers may sell the batteries below their actual costs. Price data were obtained through key expert meetings at the Energy Storage North America meeting in San Diego, CA during October 2015. This was the largest energy storage event in North America and represents state-of-the-art information.

	y_aprice	logy_aprice	price_lithium	price
y_aprice	1.0000			
logy_aprice	0.9304	1.0000		
price_lithium	0.6780	0.7122	1.0000	
price_cobalt	0.4437	0.5817	0.6275	1.00

Supplementary Table 11: Correlation matrix of battery prices and their major raw materials lithium and cobalt. Table shows the correlation for the yearly average battery price (y_aprice) and the logarithmized yearly average price (logy_aprice), as well as for the prices of lithium and cobalt. Cobalt shows a particularly low correlation to y_aprice.

Regressand	y_aprice	logy_aprice
Coef 0	α_0 = -1304.438 (719.3649)	α_0 = 1.922106*** (0.2067938)
Coef 1	α_1 = 0.4976146** (0.159299)	α_1 = 0.0001342** (0.0000458)
Coef 2	α_2 = 0.0022415 (0.0157198)	α_2 = 0.000000514 (0.000000452)
# obs	23	23
F	8.53	11.61
Prob > F	0.0021**	0.0005***
R^2	0.4602	0.5372
Adj. R^2	0.4063	0.4909

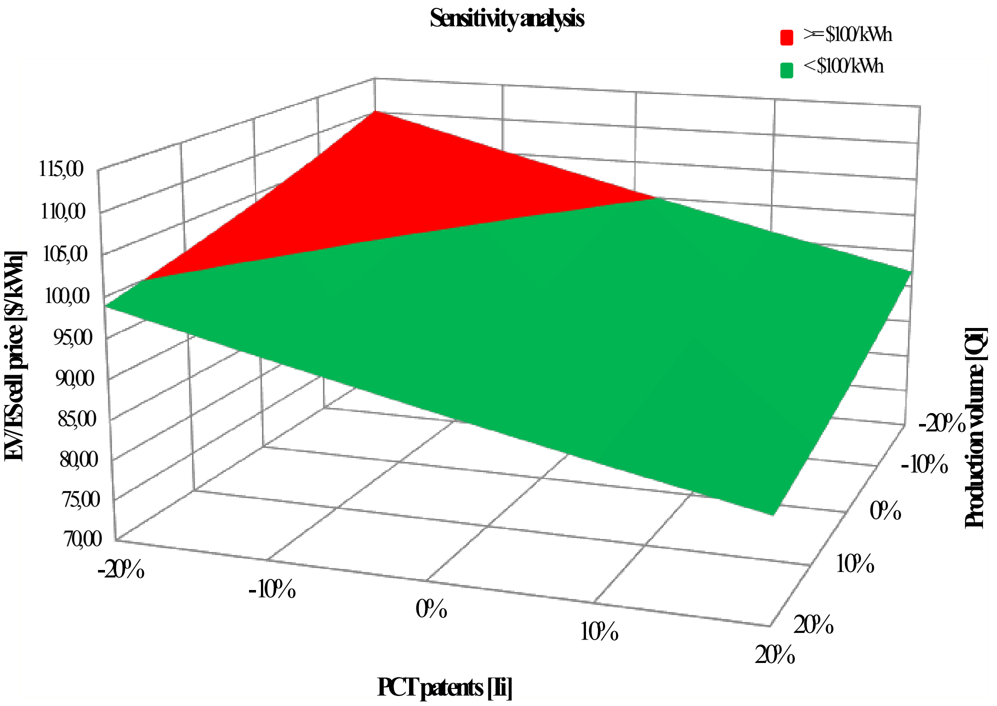
*Supplementary Table 12: Overview of key regression results incorporating prices for lithium and cobalt. Regressions were conducted for the yearly average battery price (y_aprice) and the logarithmized yearly average price (logy_aprice) with lithium prices as the first independent variable and cobalt prices as the second. Standard errors of coefficients are displayed in parentheses. P-values follow the convention: *** <0.001< ** <0.01< * <0.05. Low R^2 for Eq. 1 is desired as the regression is used to introduce the residual variable.*

Supplementary Note 2: Cost of deployment versus innovation

We investigate the tradeoff between deployment and innovation in the two-factor model.

We created a base case scenario that represents the PCT forecast as presented in the paper.

To estimate the effect of deployment versus innovation, we then scaled back patent activity to see how much deployment is necessary to achieve the cost-completive threshold target of $100/kWh storage. We find that reducing patent activity would incur significant costs to achieve necessary reductions in price through deployment alone. In summary, with 33% less patent activity from the base case of 444 patents/year, we find, an additional 306,740 MWh of deployment necessary across the world to meet a $100/kWh target. At the extreme case, withholding patent activity in the two-factor model would require an enormous 1,781,805 MWh of deployment across the world by 2020. We also estimated the opportunity cost at 143 billion dollars assuming that by multiplying the cell price by the output in MWh. This would be a significantly large investment in energy storage through deployment that would be much lessened by investing in research and deployment. It is unrealistic to expect no future patent activity, but this exercise highlights the importance of patent activity to reducing the price of energy storage technologies. Supplementary Figure 3 illustrates the tradeoff between patent activity and production volume.



Supplementary Figure 3. Sensitivity matrix for varied levels of future forecasted patent activity and production volume. We increase and decrease patents and production volumes each by +/- 20% in 2020 to see the range of conditions where EV-ES cells reach $100/kWh thresholds. We conduct a sensitivity analysis to look at different forecasting scenarios (assuming either a high level or low level of future patent activity and production volume. The prices represented in Figure 6 forecast to 2020 with varying levels of PCT patents and *production volumes. For instance, -20% PCT means that in each year (2016-2020) we decrease patent activities by 20% from the baseline data. At the same time, +20% production volume (Q_i) refers to the increase of 20% larger production volume from 2016-2020 than the baseline two-factor model. The line separating red and green represents the $100/kWh threshold of cost competitiveness.*

To achieve $76/kwh on cell level by 2020 (representing $100/kWh for the battery) the following sensitivity applies:

1. Base Case: official forecasts for the output and our PCT forecast (Supplementary Table 13)
2. -33.33% less PCT until 2020: that would require additional 306,740 MWh of output at total costs: yearly additional output multiplied by the yearly price = $ 27.6 billion cost for deployment until 2020 (Supplementary Table 14)
3. -100% less PCT until 2020: that would require additional 1,781,805 MWh of output at total costs: yearly additional output multiplied by the yearly price = $ 143.1 billion cost for deployment until 2020 (Supplementary Table 15)

Year	Cell price ($/kWh)	Output (MWh)	PCT (# patents)
2016	**124.15**	62200	444.0
2017	**109.18**	71800	444.0
2018	**96.38**	81700	444.0
2019	**85.55**	91100	444.0
2020	**76.03**	101100	444.0

Supplementary Table 13. Base Case

Year	Cell price ($/kWh)	Output (MWh)	PCT (# patents)	Output delta	Opportunity cost for delta $
2016	**110.09**	108974.4	296	46774.4	5149393696
2017	**99.77**	125793.6	296	53993.6	5386941472
2018	**90.76**	143138.4	296	61438.4	5576149184
2019	**83.01**	159607.2	296	68507.2	5686782672
2020	**76.03**	177127.2	296	76027.2	5780348016
		+75.20 %	**-33.33 %**	306740.8	**27,579,615,040**

Supplementary Table 14. Case 2: -1/3 PCT patent activity from 2016-2020

Year	Cell price ($/kWh)	Output (MWh)	PCT (# patents)	Output delta	Opportunity costs for delta $
2016	**86.61**	334014	0	271814	23541810540
2017	**83.39**	384848	0	313048	26105072720
2018	**80.51**	438729	0	357029	28744404790
2019	**78.20**	489207	0	398107	31131967400
2020	**76.04**	542907	0	441807	33595004280
		+437,00%	**-100%**	1781805	**143,118,259,730**

Supplementary Table 15. Case 3: -100% PCT patent activity from 2016-2020

Supplementary Note 3. Patent Lag & Knowledge Stock Depreciation

We investigate the effects of time lags on patents for one, two, three, and four years. We also add sensitivities to understand the effect of a “knowledge depreciation” rate, where patents in the past have smaller effects on prices today than recent patents. We also investigate a knowledge depreciation rate of 5% and 10% linear depreciation over time as included here in the supplemental materials, and find future cost reductions in the same range of the sensitivity matrix.

```
. reg Ii Qi

      Source |       SS       df       MS              Number of obs =      25
-------------+------------------------------           F(  1,    23) =   15.87
       Model |  11947178.4     1  11947178.4           Prob > F      =  0.0006
    Residual |  17310807.6    23   752643.81           R-squared     =  0.4083
-------------+------------------------------           Adj R-squared =  0.3826
       Total |    29257986    24  1219082.75           Root MSE      =  867.55

------------------------------------------------------------------------------
          Ii |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
          Qi |   480.6329   120.6356     3.98   0.001     231.0791    730.1867
       _cons |  -711.5858   430.2888    -1.65   0.112    -1601.706    178.5345
------------------------------------------------------------------------------
```

T1: Regression results for Eq. 4

```
. reg Pi Qi ni

      Source |       SS       df       MS              Number of obs =      25
-------------+------------------------------           F(  2,    22) =  213.18
       Model |  5.10558312     2  2.55279156           Prob > F      =  0.0000
    Residual |  .263441093    22  .011974595           R-squared     =  0.9509
-------------+------------------------------           Adj R-squared =  0.9465
       Total |  5.36902422    24  .223709342           Root MSE      =  .10943

------------------------------------------------------------------------------
          Pi |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
          Qi |  -.3101608   .0152164   -20.38   0.000    -.3417177   -.2786039
          ni |  -.0000881   .0000263    -3.34   0.003    -.0001427   -.0000334
       _cons |   3.797658   .0542746    69.97   0.000     3.685099    3.910216
------------------------------------------------------------------------------
```

T2: Regression results for Eq. 5

Year	**Price ($/kWh)**
2016	**124.15**
2017	**109.18**
2018	**96.38**
2019	**85.55**
2020	**76.03**

Supplementary Table 16. No patent lag, no depreciation (our model)

```
. reg Ii Qi

      Source |       SS           df       MS      Number of obs   =        25
-------------+----------------------------------   F(1, 23)        =     14.34
       Model |  5628150.68         1  5628150.68   Prob > F        =    0.0010
    Residual |  9028905.48        23  392561.108   R-squared       =    0.3840
-------------+----------------------------------   Adj R-squared   =    0.3572
       Total |  14657056.2        24  610710.673   Root MSE        =    626.55

------------------------------------------------------------------------------
          Ii |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
          Qi |   329.8858   87.12333     3.79   0.001     149.6575    510.1142
       _cons |  -500.1874   310.7556    -1.61   0.121    -1143.034    142.6596
------------------------------------------------------------------------------

. reg Pi Qi ni

      Source |       SS           df       MS      Number of obs   =        25
-------------+----------------------------------   F(2, 22)        =    205.66
       Model |  5.09643317         2  2.54821658   Prob > F        =    0.0000
    Residual |  .272591046        22  .012390502   R-squared       =    0.9492
-------------+----------------------------------   Adj R-squared   =    0.9446
       Total |  5.36902422        24  .223709342   Root MSE        =    .11131

------------------------------------------------------------------------------
          Pi |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
          Qi |   -.310152   .0154784   -20.04   0.000    -.3422523   -.2780518
          ni |  -.0001176   .0000371    -3.17   0.004    -.0001946   -.0000407
       _cons |   3.797621   .0552091    68.79   0.000     3.683124    3.912118
------------------------------------------------------------------------------
```

Year	**Price ($/kWh)**
2016	**108.88**
2017	**99.20**
2018	**84.93**
2019	**73.12**
2020	**63.03**

Supplementary Table 17. 2 years patent lag, no depreciation

```
. reg Ii Qi

      Source |       SS       df       MS              Number of obs =      25
-------------+------------------------------           F(  1,    23) =   14.78
       Model |  3608828.94     1  3608828.94           Prob > F      =  0.0008
    Residual |  5615644.82    23  244158.471           R-squared     =  0.3912
-------------+------------------------------           Adj R-squared =  0.3648
       Total |  9224473.76    24  384353.073           Root MSE      =  494.12

------------------------------------------------------------------------------
          Ii |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
          Qi |   264.1581   68.70949     3.84   0.001     122.0217    406.2945
       _cons |  -401.8521   245.0763    -1.64   0.115     -908.831    105.1268
------------------------------------------------------------------------------
```

```
. reg Pi Qi ni

      Source |       SS       df       MS              Number of obs =      25
-------------+------------------------------           F(  2,    22) =  205.71
       Model |  5.09649696     2  2.54824848           Prob > F      =  0.0000
    Residual |  .272527254    22  .012387602           R-squared     =  0.9492
-------------+------------------------------           Adj R-squared =  0.9446
       Total |  5.36902422    24  .223709342           Root MSE      =   .1113

------------------------------------------------------------------------------
          Pi |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
          Qi |  -.3101535   .0154766   -20.04   0.000      -.34225    -.278057
          ni |  -.0001491    .000047    -3.17   0.004    -.0002466   -.0000516
       _cons |   3.797627   .0552027    68.79   0.000     3.683144    3.912111
------------------------------------------------------------------------------
```

Year	**Price ($/kWh)**
2016	**101.49**
2017	**82.11**
2018	**74.03**
2019	**61.71**
2020	**51.52**

Supplementary Table 18. 3 years patent lag, no depreciation

```
. reg Ii Qi

      Source |       SS       df       MS              Number of obs =      24
-------------+------------------------------           F(  1,    22) =   19.10
       Model |  2583591.28     1  2583591.28           Prob > F      =  0.0002
    Residual |  2976272.68    22  135285.122           R-squared     =  0.4647
-------------+------------------------------           Adj R-squared =  0.4404
       Total |  5559863.96    23  241733.216           Root MSE      =  367.81

------------------------------------------------------------------------------
          Ii |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
          Qi |   277.0633   63.40042     4.37   0.000     145.5789    408.5478
       _cons |  -570.1969   230.5087    -2.47   0.022    -1048.243   -92.15103
------------------------------------------------------------------------------
```

```
. reg Pi Qi ni

      Source |       SS       df       MS              Number of obs =      24
-------------+------------------------------           F(  2,    21) =  285.58
       Model |  4.28175764     2  2.14087882           Prob > F      =  0.0000
    Residual |   .15742588    21   .00749647           R-squared     =  0.9645
-------------+------------------------------           Adj R-squared =  0.9612
       Total |  4.43918352    23  .193007979           Root MSE      =  .08658

------------------------------------------------------------------------------
          Pi |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
          Qi |  -.3548888   .0149246   -23.78   0.000    -.3859262   -.3238515
          ni |  -.0001267   .0000502    -2.53   0.020     -.000231   -.0000224
       _cons |   3.965864   .0542623    73.09   0.000      3.85302    4.078709
------------------------------------------------------------------------------
```

Year	**Price ($/kWh)**
2016	**116.31**
2017	**94.14**
2018	**78.04**
2019	**71.11**
2020	**60.46**

Supplementary Table 19. 4 years patent lag, no depreciation

```
. reg Ii Qi

      Source |       SS       df       MS              Number of obs =      25
-------------+------------------------------           F(  1,    23) =   16.52
       Model |  9017645.27     1  9017645.27           Prob > F      =  0.0005
    Residual |  12554724.5    23  545857.586           R-squared     =  0.4180
-------------+------------------------------           Adj R-squared =  0.3927
       Total |  21572369.8    24   898848.74           Root MSE      =  738.82

------------------------------------------------------------------------------
          Ii |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
          Qi |   417.5682   102.7355     4.06   0.000     205.0436    630.0927
       _cons |  -610.5825   366.4418    -1.67   0.109    -1368.625    147.4601
------------------------------------------------------------------------------

. reg Pi Qi ni

      Source |       SS       df       MS              Number of obs =      25
-------------+------------------------------           F(  2,    22) =  216.23
       Model |   5.1091139     2  2.55455695           Prob > F      =  0.0000
    Residual |  .259910318    22  .011814105           R-squared     =  0.9516
-------------+------------------------------           Adj R-squared =  0.9472
       Total |  5.36902422    24  .223709342           Root MSE      =  .10869

------------------------------------------------------------------------------
          Pi |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
          Qi |  -.3101643   .0151141   -20.52   0.000    -.3415091   -.2788196
          ni |  -.0001048   .0000307    -3.41   0.003    -.0001685    -.000041
       _cons |   3.797672   .0539097    70.45   0.000      3.68587    3.909474
------------------------------------------------------------------------------
```

Year	**Price ($/kWh)**
2016	**126.28**
2017	**111.70**
2018	**99.80**
2019	**90.83**
2020	**86.08**

Supplementary Table 20. 10% depreciation rate, no patent lag

```
. reg Ii Qi

      Source |       SS       df       MS              Number of obs =      25
-------------+------------------------------           F(  1,    23) =   15.95
       Model |  11875828.6     1  11875828.6           Prob > F      =  0.0006
    Residual |  17129982.8    23  744781.861           R-squared     =  0.4094
-------------+------------------------------           Adj R-squared =  0.3838
       Total |  29005811.4    24  1208575.47           Root MSE      =  863.01

------------------------------------------------------------------------------
          Ii |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
          Qi |   479.1956   120.0039     3.99   0.001     230.9486    727.4425
       _cons |  -711.9343   428.0356    -1.66   0.110    -1597.393    173.5248
------------------------------------------------------------------------------
```

```
. reg Pi Qi ni

      Source |       SS       df       MS              Number of obs =      25
-------------+------------------------------           F(  2,    22) =  213.49
       Model |  5.10593885     2  2.55296942           Prob > F      =  0.0000
    Residual |  .263085368    22  .011958426           R-squared     =  0.9510
-------------+------------------------------           Adj R-squared =  0.9465
       Total |  5.36902422    24  .223709342           Root MSE      =  .10935

------------------------------------------------------------------------------
          Pi |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
          Qi |  -.3101612   .0152061   -20.40   0.000    -.3416968   -.2786256
          ni |  -.0000886   .0000265    -3.35   0.003    -.0001435   -.0000337
       _cons |   3.797659    .054238    70.02   0.000     3.685176    3.910142
------------------------------------------------------------------------------
```

Year	**Price ($/kWh)**
2016	**114.11**
2017	**99.50**
2018	**87.32**
2019	**76.87**
2020	**68.01**

Supplementary Table 21. 5% depreciation rate, no patent lag

```
. reg Ii Qi

      Source |       SS           df       MS      Number of obs   =        25
-------------+----------------------------------   F(1, 23)        =     15.09
       Model |  4343851.49         1  4343851.49   Prob > F        =    0.0007
    Residual |  6618723.55        23  287770.589   R-squared       =    0.3962
-------------+----------------------------------   Adj R-squared   =    0.3700
       Total |    10962575        24   456773.96   Root MSE        =    536.44

------------------------------------------------------------------------------
          Ii |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
          Qi |   289.8133   74.59402     3.89   0.001     135.5038    444.1228
       _cons |  -432.2306   266.0655    -1.62   0.118     -982.629    118.1678
------------------------------------------------------------------------------


. reg Pi Qi ni

      Source |       SS           df       MS      Number of obs   =        25
-------------+----------------------------------   F(2, 22)        =    208.30
       Model |  5.09971536         2  2.54985768   Prob > F        =    0.0000
    Residual |  .269308858        22  .012241312   R-squared       =    0.9498
-------------+----------------------------------   Adj R-squared   =    0.9453
       Total |  5.36902422        24  .223709342   Root MSE        =    .11064

------------------------------------------------------------------------------
          Pi |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
          Qi |  -.3101558   .0153849   -20.16   0.000    -.3420622   -.2782494
          ni |  -.0001392   .0000431    -3.23   0.004    -.0002285   -.0000499
       _cons |   3.797637   .0548758    69.20   0.000     3.683832    3.911442
------------------------------------------------------------------------------
```

Year	**Price ($/kWh)**
2016	**107.27**
2017	**99.84**
2018	**87.05**
2019	**75.56**
2020	**66.22**

Supplementary Table 22. 10% depreciation, 2 years patent lag

Supplementary References:

1. Will, F. G. Impact of lithium abundance and cost on electric vehicle battery applications. *Journal of Power Sources*, **63**, 23-26 (1996).

2. US DOE. Critical Materials Strategy. http://energy.gov/sites/prod/files/DOE_CMS2011_FINAL_Full.pdf 2011).

Chapter 4: Energy return on investment (EROI) of mini-hydro and solar PV systems designed for a mini-grid

Abstract:

With dramatic cost declines and performance improvements, both mini-hydropower and solar photovoltaics (PV) now serve as core options to meet the growing demand for electricity in underserved regions worldwide. We compare the net energy return on energy invested (EROI) of mini-hydropower and solar electricity using five existing mini-hydropower installations in northern Thailand with grid-connected solar PV simulations. Both assessments use a life cycle perspective to estimate the EROI. We find that distributed mini-grids with penetrations of solar PV up to 50% of annual generation can exceed the EROI of some fossil-based traditional centralized grid systems. The analysis will help planners and engineers optimize mini-grids for energy payback and utilize local resources in their design. The results suggest higher EROI ratios for mini-hydropower plants than solar PV, though mini-hydropower plants typicall yield lower EROI ratios than their large-scale hydropower counterparts.

1. Introduction

Mini-hydropower[1] and solar PV electricity are two potential sustainable sources of electricity that may empower communities to generate their own electricity and reduce energy imports. Furthermore, there is an increased emphasis on improving electricity reliability and resilience through the use of distributed energy resources in a functioning mini-grid [Alstone et al., 2015; Halu et al., 2016]. Thailand is facing growing demand for electricity and remains electricity supply constrained as referenced in the most recent Thai Power Development Plan [Thai PDP, 2015]. To accommodate this increased electricity demand while maintaining environmental sustainability, increased attention has focused on decreasing Thailand's reliance on electricity imports, since more than 60% of its primary energy for electricity generation comes from abroad [Tongsopit & Greacen, 2013]. Thailand historically set up pilot mini-grid research projects in island regions, including Koh Jig, designed in 2004 as a prototype for island sustainability [Smith et al., 2015]. The mountainous stretches of northern Thailand similarly face rising costs in expanding centralized transmission investments and therefore have generated interest by the utilities to create mini-grid systems that utilize distributed renewable resources. Therefore, sustained interest in maintaining high penetrations of renewable energy in the grid play a key role in advancing policy support for utilizing existing mini-hydro power plants and constructing new solar plants in new mini-grid test-bed research hubs.

Large-scale hydropower, while key to many previous national development efforts, historically has generated negative social and environmental impacts by displacing people from their homes, altering livelihoods, and destroying habitats for many river-borne species. For instance, downstream impacts of hydropower development not only effect one country as in the case of Thailand, but have drastically reshaped regional watersheds [Ziv et al., 2012]. Small run-of-river hydropower applications do not entail the same negative externalities as mega-dams yet contribute to basic electricity supply needs [Suwanit & Gheewala, 2011]. However, during the summer, mini-hydropower experiences reduced levels of generation. Seasonal variability is

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[1] We define mini-hydropower as run-of-river hydroelectric power plants with a peak capacity between 200-6000 kW [Paish, 2002].

expected to increase with climate change [Pittock, 2010]. This makes solar PV an attractive technology to complement generation from mini-hydropower and provide supplementary electricity supply capacity. The cost of solar electricity has declined significantly enabling solar PV to emerge as a cost-effective energy source for the region. New innovations in smart control systems, battery storage, and mini-hydropower technologies are facilitating the ease at which grid operators can balance power systems with high penetrations of intermittent renewables.

Net energy analysis presents an important tool for understanding the amount of energy we need to spend to make energy. The EROI in the context of electricity generating technologies provides an accounting framework to understand the net production of electrical energy divided by the input primary energy to produce such devices [Carbajales-Dale et al., 2014]. This EROI metric is used as a tool comparable to other metrics developed and used in net energy analysis, namely energy payback ratio (EPR) and life-cycle inventories. The main purpose of EROI is to measure energy diverted from society to make available energy for society [Arvesen & Hertwich, 2015]. For instance, previous protocols developed to understand EROI of fuels highlights the advantages of EROI analysis. First, it provides a standard framework to compare the substitutability of different fuels (historically, corn ethanol and gasoline). Second, it measures resource quality. Third, it provides insights into net energy gains when extracting energy from resources, and lastly as EROI can change over time, we can understand technological development and resource changes [Murphy et al., 2011]. Further, there is almost no energy return on investment (EROI) data for mini-hydropower projects and this paper uses real manufacturing inputs and electricity outputs from northern Thailand to evaluate the energy return on investment (EROI) of mini-hydro and solar PV systems designed in a mini-grid configuration. Few studies have compared the energy requirements of mini-grids and we investigate the role of solar and mini-hydro in improving overall mini-grid sustainability. From a net energy perspective, there is a growing need to understand more about the complementarity of different renewable technologies in resource-constrained areas due to seasonal changes in resource availability. Newly developed production practices in solar electricity improve its energy payback ratio, and could further improve environmental considerations depending on the manufacturing locations [Murphy et al, 2011]. Few studies characterize the net energy ratio of mini-hydro power plants because they view the analysis as arbitrary and geographically dependent [Gupta & Hall, 2011]. Table 1 summarizes reported EROI for various energy technologies and fuels as reported in the literature, however as noted, each needs further study as often EROI varies by geographic location and a lack of real data, to which this study addresses the need for realistic data by using real, observed mini-hydropower embodied energy and electric generation [Hall et al., 2014].

Table 1. Summary of reported mean EROI values for various energy technologies as reported in the literature (Source: Hall et al., 2014).

Power generation technology	**Mean EROI**
Coal	46
Natural gas	7
Nuclear	13
Hydroelectric (large)	84
Geothermal	9
Wind	18
Solar PV	10

Mini-hydro plants may vary in terms of output due to geographic variables, however, net energy analysis remains an important tool, especially in energy supply constrained areas, where local materials exist to construct mini-hydro power facilities, as done in northern Thailand. Furthermore, simply because few studies investigated the net energy payback ratio of mini-hydropower plants does not mean the results will be meaningless as it helps policymakers and practitioners understand the comparative costs and benefits of expanding electricity supply when choosing between renewable energy and fossil fuels. We seek to understand the implications of energy return on energy invested for mini-hydropower plants and solar PV because they will become increasingly important distributed energy resources around the world as renewable, cost-effective sources of electricity. Therefore, it becomes useful in the practice of sustainability analysis to compare the EROI of run-of-river mini-hydropower plants with solar PV and storage systems to help determine appropriateness for use in rural settings of northern Thailand. As both renewable technologies have environmental life-cycle impacts significantly less than conventional energy sources, the analysis provides insights for decision-makers in Thailand and across ASEAN to consider when developing distributed generation (DG) power [Suwanit & Gheewala, 2011; Kittner et al, 2013]. Thailand faces renewed energy security issues and this analysis can provide some insights on how to use existing energy and resources in an efficient matter to get the most energy output for energy invested in developing mini-hydro or solar PV systems [Tongsopit et al., 2016].

The remote mountainous regions of northern Thailand pose physical challenges for transmitting centralized electricity loads due to the steep physical terrain and lack of existing infrastructure. Therefore, both mini-hydro and solar power can serve as localized distributed generation options that feed the electricity grid and can improve reliability. This can be achieved by incorporating mini-hydro or solar projects into a mini-grid system or connecting the projects to the Provincial Electricity Authority (PEA) managed grid using AC inverters and other balance-of-system components to improve the flexibility of a mini-grid. This study evaluates a hypothetical islanding setup where new solar PV generation complements existing mini-hydropower stations in a new mini-grid design, that includes battery energy storage (BESS) or imported PEA-managed grid electricity to address intermittency issues. Figure 1 details the mini-grid setup.

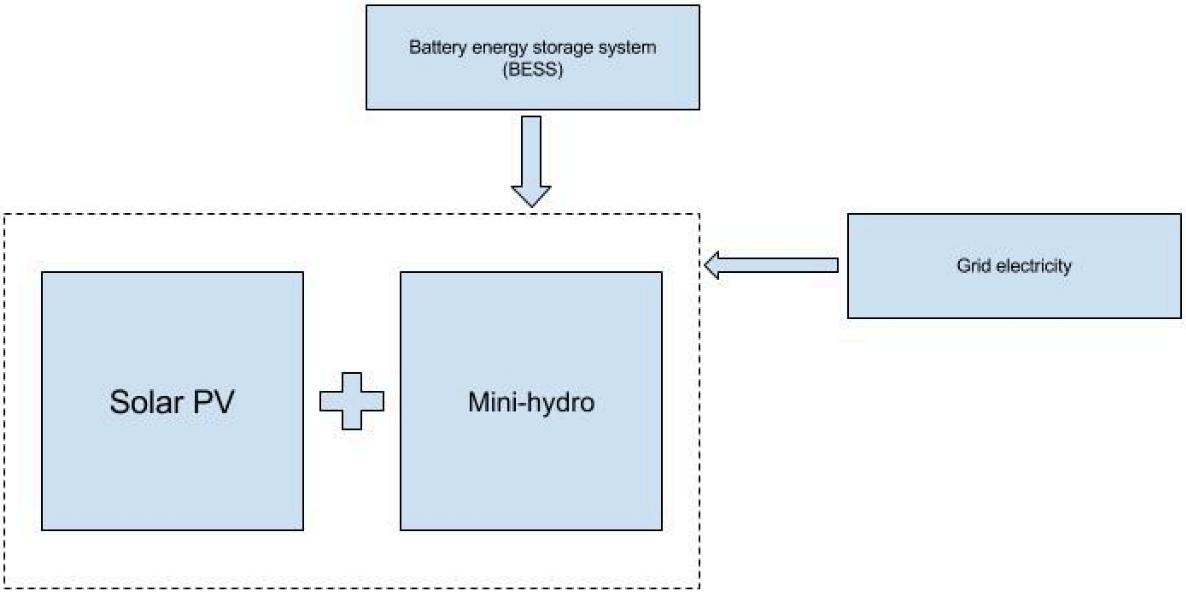

Figure 1. Hypothetical islanding set-up where new solar PV generation complements existing mini-hydropower installations in mini-grid design supplemented by grid and/or BESS electricity.

Both mini-hydro and solar PV technology receive policy support through the state-owned electricity authority. Thailand will seek to have 6 GW of solar online by 2036 and 324 MW of "small-scale" hydropower. Additionally, the development of mini-hydro power in Thailand remains below target levels and must catch up to meet the desired policy goals [Tongsopit & Greacen, 2013; Tongsopit, 2015]. Solar has exceeded renewable electricity installed capacity targets due to lowered module prices imported from China and the large availability of inexpensive land to connect utility-scale solar projects on the grid. The solar power adder program received so many applications it reached its cap by the end of 2013. For instance, growth of grid-connected solar PV in Thailand grew 211% per year during 2007-2013 stopping at 782 MW of utility-scale solar. Further analysis showed that distributed rooftop solar PV in Thailand could reach $2.12 USD/W according to the National Energy Policy Commission, with utility-scale installations less than $2 USD/W [Tongsopit et al, 2015]. Financial support through feed-in tariffs also provide between $0.19-0.22 USD/kWh, heavily promoting the use of solar in Thailand. Even further, Thailand's adder program has a $0.05 USD/kWh special adder for diesel replacement. New business models, including community solar arrays are becoming possible in Thailand [Tongsopit et al 2016]. Increasingly common in the context of grid extension and rural electrification, mini-hydropower and solar PV-hybrid systems are implemented in conjunction with each other. Some types of mini-hydropower can provide dispatchable, and critical baseload generation to mitigate the variability of PV electricity. The combined suite of technologies emerges as a more common option for remote mountainous areas, with special relevance for northern Thailand due to abundant small rivers and mountainous terrain.

A growing body of work has investigated the potential value of net energy analysis [Murphy & Hall, 2010, 2011; Gupta & Hall, 2011; Carbajales-Dale et al., 2014]. The lack of consensus among researchers on the EROI of variable technologies including hydropower warrants further study. Therefore, we aim to elucidate some of the nuances for mini-hydropower plants specifically. Most studies focus on large-scale hydropower operations [Weißbach et al., 2013]. Other studies assume the hydropower plants to last very long on the order of 100-200 years, leading to potential overestimates of the energy returned on energy invested [Weißbach et al., 2013; Atlason & Unnthorsson, 2014]. Using information from existing mini-hydropower plants we can estimate the EROI. Due to a growing interest in distributed energy resources, particularly small-scale run-of-river non-reservoir based hydropower power plants, the study could easily contribute to these developments across Southeast Asia. Furthermore, more research is needed for growing hybrid mini-grid systems that utilize solar PV power generation alongside mini-hydropower in place of expanding transmission lines and building large new centralized plants.

There is a wide reported range of energy payback ratios for solar PV systems [Murphy & Hall, 2010; Raugei et al., 2012]. Some problems stem from the misapplication of life cycle-based inventory energy data for EROI studies [Arvedsen & Hertwich, 2015]. Others reflect the improvements in manufacturing technology and PV performance over time [Raugei et al., 2012]. Further methodologies dispute the inclusion of expressing the electricity returned to society by PV in terms of primary energy equivalent, which makes PV directly competitive with conventional fossil fuels and sometimes fares better in terms of EROI [Raugei et al., 2012]. Drawing on recent literature, this study elucidates a higher energy return on energy invested than typically perceived for solar PV and the way that both mini-hydro and solar can contribute to sustainability goals. Previous research indicates a need for more thorough investigations of the EROI on different systems [Murphy & Hall, 2010; Gupta & Hall, 2011]. Thus, the study clarifies many recorded values. The rapid decrease of the cost for solar electricity has altered production practices such that new modules have vastly different EROIs than modules from five-to-ten years ago.

Additionally, the EROI could help inform future systems-scale studies that investigate an entire mini-grid—potentially consisting of mini-hydro, solar, bioenergy, and battery storage. In the future, developing countries may become highly reliant on mini-grids especially in remote or mountainous areas and the total environmental impacts or energy ratios may become useful to understand how renewable energy technologies can complement or detract from each others' energy inputs and outputs when working together. This study forms the basis of comparison for mini-hydro and mini-grid-connected solar electricity, since technology assessments are rapidly changing. Furthermore, new capacity expansion is experience an emergence of decentralized networks for off-grid and on-grid electricity systems [Alstone et al., 2015].

2. Materials and Methods

2.1 Goal and Scope

The goal of this study is to evaluate and compare the EROI of mini-hydropower and solar photovoltaic plants in northern Thailand. The methodology for energy return on investment (EROI) utilizes a life-cycle approach [Raugei et al., 2012; Suwanit & Gheewla, 2011; Kittner et al, 2012; Radaal et al., 2011]. That means that we investigate the life-cycle embodied input energy for each technology and the usable electricity generated as energy output for the EROI metric. The study estimates the net cradle-to-grave electricity production and required input energy during the lifetime of both mini-hydro and solar PV systems and we simulate the mini-grid EROI using a scenario-based approach.

2.2 Study Sites

The five mini-hydropower sites analyzed here are located in northern Thailand. They range in capacity from 1,150-5,100 kW. These plants produce electricity with an average capacity factor ranging from 40-50%[2]. The plant details are summarized in Table 2. For the purposes of this EROI calculation, we average the five study sites and assume they are representative of typical run-of-river mini-hydropower plants in Thailand. We report a range of EPR values that represent a lower and upper bound for the run-of-river plants. The mini-hydropower plants are all located across northern Thailand and represent what we would expect future run-of-river developments may look like if new turbines are built in the coming decade. There is a vast run-of-river resource in the mountains of northern Thailand. In Sukhothai province, at Ramkhamhaeng National Park there already exists a sample PV-mini-hydro-battery hybrid system as a proof of concept to expand to other mini-hydro sites along different rivers in northern Thailand. Table 2 explains the locations of the five mini-hydropower plants that we consider along with their peak capacity and generator type for grid connection.

Table 2. Locations of five mini-hydropower plants in northern Thailand, their peak capacity, and composition.

Study Site	Geographic Location	Capacity (kW)[2]	Generator type	Land area	Design flow rate (m^3/s)	Weir dimensions	Penstock material and dimensions	Water gate and screens
Mae Thoei	Om Koi, Chiang Mai	2,250	Synchronous	12 ha	2 m^3/s	Concrete; 2m x 18m	Steel; 1 m x 404 m	14 sets
Mae Pai	Pai, Mae Hong Son	Two sets of 1,250 kW	Synchronous	23 ha	1.39 m^3/s	Concrete; 3.5m x 21.5m	Steel; 1.15 m x 182 m	15 sets
Mae Ya	Jom Thong, Chiang Mai	1,150	Induction	6.4 ha	1.73 m^3/s	Concrete; 3.6m x 46m	Steel; 0.9 m x 360 m	13 sets
Nam San	Phu Rua, Loei	3,000	Synchronous	9.6 ha	4.36 m^3/s	Concrete; 4 m x 55 m	Steel; 1.82 m x 250 m	19 sets
Nam Man	Dan Sai, Loei	5,100	Synchronous	7.3 ha	6.0 m^3/s	Concrete 4 m x 35.5 m	Steel; 1.51 m x 304 m	17 sets

We analyze the mini- hydropower plants using real, historical data. The solar sites are simulated to be located next to the mini-hydro sites, as if to represent a future hybrid mini-grid system that combines solar photovoltaics with run-of-river mini-hydropower and battery storage. A typical solar installation in northern Thailand averages approximately 4.88 $kWh/m^2/day$ or about 1,750 $kWh/m^2/year$ on a 30° south-facing plane. We also simulate a 3MWp grid-connected solar installation with balance-of-system components and AC inverter in the same

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[2] Note: The average capacity factor for these plants is 40-50%, which averages that of similar-sized plants in Afghanistan (30-60%) or Malaysia (60%) [Suwanit & Gheewala, 2011]

study area. The solar PV output is simulated using PVSYST for electricity output over the course of the lifetime [Mermoud, 2016]. The mini-hydropower plants and simulated solar installation comprise a potential mini-grid that would be used to meet growing demand for electricity without resorting to importing more electricity or expanding transmission capacity.

2.3 Technology

Run-of-river mini-hydropower plants, single-crystalline, multi-crystalline, and amorphous silicon solar PV are compared using net energy payback ratios. The run-of-river hydropower plants consist of two Turgo turbines except the Mae Ya mini-hydropower plant, which features an induction motor.

3. Methodology

We use tools that incorporate life cycle thinking to compare the energy ratio of mini-hydropower and solar PV. The energy return on energy invested (EROI) is the ratio of the total energy produced during a system's normal lifespan, divided by the energy required to build, maintain, and power the system. A high ratio typically indicates good energetic and environmental performance. Data come from literature values of the single-crystalline and amorphous silicon PV panels. The ratio focuses on understanding the ratio of energy output compared to energy required to construct an electricity generation technology. The methods have been developed through the literature [Gupta & Hall, 2011; Raugei et al., 2012; Hall et al., 2014]. The EROI included the use of life-cycle inventory data for the energy lifetime output and includes pre-construction land clearance, construction of the mini-hydropower plant and solar PV system, transportation of materials, operational energy production, and demolition.

This equation (1) takes the input energy for each technology and sums across the manufacturing and process energy. It also estimates the electric energy output and divides the lifetime energy output by the input energy for each technology system. We use a standard EROI approach for comparability.

$$Energy\ Returned\ on\ Energy\ Invested\ (EROI) = \frac{\left(\frac{E_{lifetime\ output}}{\eta}\right)}{E_{materials} + E_{manufacturing} + E_{transport} + E_{install} + E_{end-of-life}} \tag{1}$$

The lifetime of the mini-hydro power plant is assumed to be 50 years whereas the solar PV installation has an expected lifetime of 30 years. The life of the mini-hydro power plant is a more conservative estimate compared to recent studies that have used lifetimes of 100-200 years. Potential limitations include that we assume no physical degradation of the panels or mini-hydropower. The PV systems include frames, mounting, cabling, and inverter, but exclude embodied energy for maintenance or recycling.

3.1 System Boundary

The energy included for construction of the mini-hydropower plants includes the weir, power intake, headrace, screen, penstock, river outlet, surge tank, and power house. The analysis includes energy estimated for the construction of all components listed and transportation fuel. The energy embodied in the energy return on energy invested includes energy of the materials, manufacturing, transport, installation, and end-of-life as detailed in equation 1.

Figure 2 details the components of the embodied manufacturing energy required for mini-hydropower and solar PV construction in this study. The EROI metric uses this information, in addition to the land clearance, transportation, and installation energy required to use mini-hydropower and solar PV in a mini-grid system.

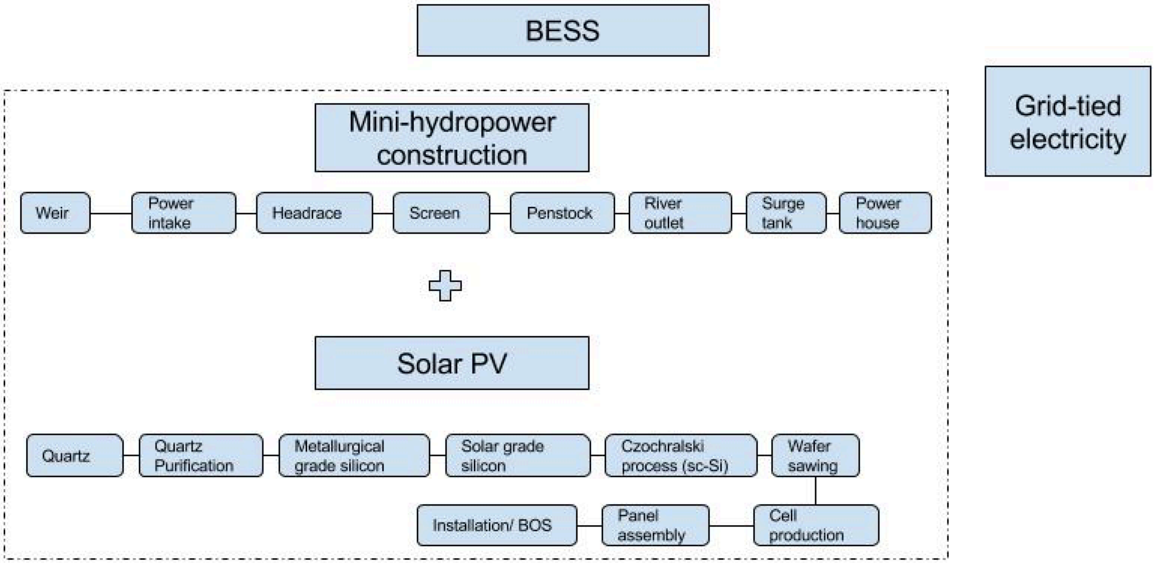

Figure 2. System boundaries for EROI analysis including individual components of mini-hydropower and solar PV systems considered for manufacturing energy required.

3.2 Mini-hydropower

Table 3 summarizes the energy consumption across various life cycle stages for five different mini-hydropower plants. The plants are located in remote areas, accounting for the variation of energy consumed in transportation stages. They also use TwinJet Turgo Impulse Turbine technologies and are synchronous generators, except for the Mae Ya site which uses an induction motor. Energy for construction includes land clearances and preparation before constructing the mini-hydropower plant. Also, the manufacturing energy includes the weir, intake, headrace, penstock and power house. Data for construction information comes from construction invoices and site visits. Nam Man and Nam San plants include tunnel construction. The other plants are fixed in concrete. Energy requirements were calculated from the bill of and site visits by discussing with project engineers and operators. The transportation energy is estimated using variety of scenarios, given the mountainous terrain and remote location of some of the plants, transportation could play a significant role in embodied energy calculations. Operation and maintenance (O&M) embodied energy includes normal maintenance and replacement of turbines, spear tips and nozzles, lubricant oil, epoxy paint, and seal plates, assuming a 25-year lifetime on turbines and spear tips and a 10 year lifetime of lubricant oil, paint, and seal plates.

Table 3. The description of energy used in each stage of the mini-hydropower plant and EROI calculation [Suwanit & Gheewala, 2011]

Description	Range of energy consumed for five mini-hydropower plants
Electricity produced in normal life span (MJ)	664,401,600 - 3,837,301,200
Energy for transportation (MJ)	6,445,987-72,400,574
Energy for construction (MJ)	1,319,984-9,133,978
Energy for operation (MJ)	1,587,917-9,554,879
Energy for demolition (MJ)	568,814-2,431,111
EROI	41-78

The reported range (41-78) of the energy returned on energy invested (EROI) for the mini-hydropower power plant results in a ratio that is quite positive and nearly to the scale of widespread fossil fuel plants including natural gas and coal. The EROI for solar PV in our simulation is not of the same scale as the mini-hydropower plant, which is to be expected, yet remains positive.

Table 4 highlights the different effects of expanding lifespan of the mini-hydropower plant and reducing the transportation energy cost for moving materials to construct mini-hydropower plants. For instance, by manipulating the lifespan and the transportation energy costs for building a mini-hydropower plant, one could achieve an EROI of 145-284, which is quite high and more than four times greater than the base case under normal assumptions. However, this gets at an important point and probably helps explain previous literature values of EROI that utilize much higher estimated life spans for mini-hydropower plants that might not be as realistic, especially in an era of a rapidly changing energy landscape from centralized plants to distributed energy resources. Other aspects of the EROI calculation for mini-hydropower plants contain aspects of uncertainty, but we feel these parameters are contributing the most to the variation of previously published literature values, that also primarily focus on run-of-river hydropower, or larger-scale plants.

Table 4. Effects of lifespan and transportation energy on EROI for mini-hydropower.

Scenarios	Range of energy payback ratio (EPR)
Scenario 1: Base case, 50 year lifespan and normal transportation	41-78
Scenario 2: 50 year lifespan and 50% reduction of transportation energy	67-108
Scenario 3: 100 year lifespan and normal transportation	86-170
Scenario 4: 100 year lifespan and 50% reduction of transportation energy	145-284

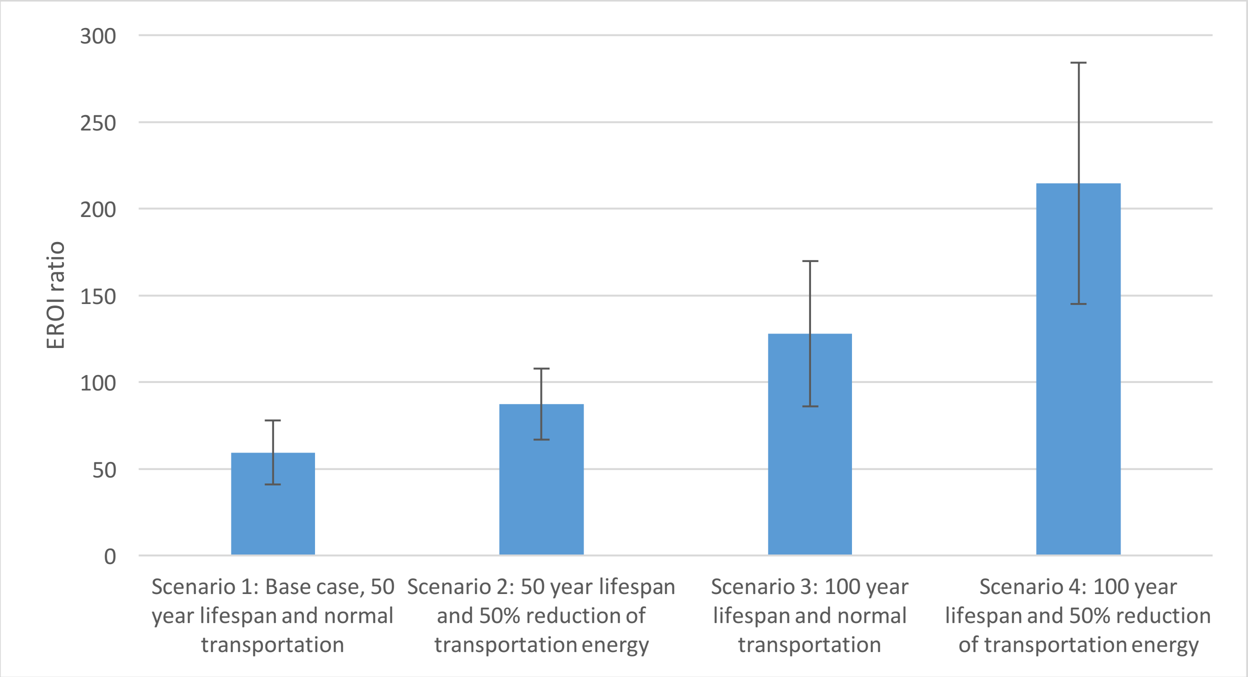

Figure 3. Sensitivity of transportation energy on EROI ratio for mini-hydropower plants.

Figure 3 highlights the significant role transportation plays in the life-cycle embodied energy of mini-hydropower plants. Reducing transportation distances to half would increase the EROI ratio by 40-70% (67-108). Construction plays the second largest contributor to life-cycle embodied energy. The implication here is that since EROI for mini-hydropower remains highly sensitive to the transport of the materials necessary to construct the plant and construction processes, more attention should be placed in a localized zone on using less energy intensive materials and shorter distances to move parts. Also, this implies that from an environmental perspective, construction managers should heed attention to site selection of mini-hydropower projects to reduce wasted energy and improve design and implementation of projects. Since previous peer-reviewed studies have used considerably longer lifespans for the mini-hydropower plants, it became interesting and useful to understand the effect of lifespan on the EROI for mini-hydropower. We consider a number of scenarios for instance, by doubling the expected lifespan of the plant to 100 years, the EROI would become 86-170, which is a 120-150% increase.

3.3. Solar photovoltaics

For the solar PV plants, we use literature values for the manufacturing of different panels taken from life-cycle manufacturing energy inventories [Kittner et al, 2013]. Because transportation plays a smaller role in the overall embodied energy requirements to manufacture and set up solar photovoltaic technologies, we do not account for the difference between installing the panels in a mountainous terrain versus a flat area. However, the output energy that is simulated would be captured through the level of solar insolation geographically. The EROI calculation includes the energy for construction and then uses PVSYST software to simulate the electricity generated during its lifetime. Though PV sometimes is not utilized in the system, it will not affect the EROI calculation, because during times of surplus electricity in the grid, there is available energy. If it is not utilized, however, that is a lack of efficiency in grid operations and management, and will not significantly change the EROI of the PV system itself. When we calculate the EROI of the mini-grid system in it's entirety however, this calculation assumes a well-managed grid that utilizes solar electricity as long as there is load to support the amount of solar installed. The mini-grid system takes into account solar variability because we approximate the amount of solar electricity utilized within the mini-grid over a period of 8,760 hours.

Life-cycle inventory and energy estimation tools are derived from manufacturing databases including ecoinvent and literature searches [Raugei et al., 2012; Kittner et al., 2013].

Table 5. Range of values obtained for embodied energy in construction of PV modules, LCI data from ecoinvent database and literature (Raugei et al., 2012; Kittner et al., 2013).

Conditions	Single-crystalline PV	Multi-crystalline PV	Amorphous-silicon PV
Insolation (kWh/m^2-yr)	1,750	1,750	1,750
Efficiency	15%	13%	7%
Energy for construction (MJ/m^2)	2,440-4,070	2,220-3,870	640-1,060
Performance Ratio	0.75	0.75	0.75
System Lifetime (years)	30	30	30
EROI	6-12	6-12	11-30

We simulate the EROI for three different types of solar PV technologies, single-crystalline, multi-crystalline, and amorphous-silicon thin-film PV. The difference in technology is important because in tropical conditions like Thailand, often times amorphous-silicon thin-film panels can be preferred due to their predilection for diffuse radiation rather than direct insolation [Kittner et al., 2013]. The conditions for the northern Thailand sites are modelled using PVSYST and literature data. The energy for construction and assembly are summarized in Table 5 along with the estimated range for EROI. These estimates are in line with other estimates for EROI of solar PV in other regions. Recent studies including Barnhart et al. 2013, determine a new metric, energy stored on invested (ESOI) (Barnhart & Benson, 2013; Barnhart et al., 2013). For large-scale pumped hydro storage systems, they find that there could be an ESOI ranging from 210-830 based on their assumptions [Weißbach et al, 2011; Barnhart & Benson, 2013; Pellow et al, 2015]. This would drastically improve the ability for solar PV to increase its own EROI, when coupled in a hybrid system that also utilizes pumped hydro storage. In fact, it could suggest that future systems should be designed to accommodate some level of pumped hydro storage, solar photovoltaics, and run-of-river mini-hydropower plants for sustainability.

In addition to EROI, the energy stored on energy invested (ESOI) emerges as a particularly relevant metric for estimating the EROI of a flexible and adaptive mini-grid design. This relevance occurs because often times grid operators must backstop intermittent solar PV or mini-hydropower generators with some form of energy storage. Energy stored on energy invested for the purposes of this research study are reported from the literature. We define ESOI as in previous studies [Barnhart 2013; Pellow 2015]. Table 6 details the ESOI values common in literature used in this analysis for various energy storage technologies including lithium-ion batteries and vanadium-redox flow batteries.

$$\mathrm{ESOI}_e = \frac{[\text{Energy discharged over lifetime}]}{[\text{Life} - \text{cycle manufacturing energy requirement}]}$$

Table 6. Energy stored on invested from literature values for various battery technologies and pumped hydro (Adapted from Pellow et al., 2015).

Storage technology	**ESOI**
Lithium-ion battery	35
Sodium sulphur battery	26
Vanadium-redox flow battery	14
Zinc-bromine flow battery	15
Lead-acid battery	5.8
Pumped hydro storage	830

The combination of EROI and ESOI metrics elicit useful thought experiments as grids change to utilize variable renewable generators and we can begin to compare the EROI of mini-grids with centralized grids.

3.4 EROI for mini-grid

We investigate the combined EROI of a mini-grid using the historic data from mini-hydropower plants in operation, simulated solar PV estimates, and literature approximates of battery electricity storage and traditional grid-tied electricity. This helps understand the net energy resources gained from designing mini-grids and can serve as a comparison to national, centralized grids. However, we ignore balance of system components and principally focus on the EROI of the electricity generating and storage technologies themselves, which remains a limitation of this particular analysis. However, based on the differing distributed electricity supply mix, we can still compare the results with centralized traditionally designed grids.

Figure 4 presents the EROI for three solar photovoltaic technologies, a lower-bound estimate for mini-hydropower turbines, and a range of EROI values for varying penetrations of solar PV in a mini-grid setup combined with mini-hydropower. The scenarios detailed investigate the changing EROI based on electricity used in a grid situation. We investigate different penetrations of electricity generated annually on a mini-grid, one with 20% of annual generation coming from solar PV and one with 50% of total annual electricity generation from solar PV. We then run sensitivity based on PV technology. The remaining 70% or 20% of annual electricity generation comes from mini-hydropower in this case. We also toggle whether the system accounts for intermittency on an hourly basis using a lithium-ion battery storage device or the central grid existing in northern Thailand which utilizes mostly coal generation from Mae Moh lignite mine-mouth plant. The results suggest that from an EROI basis, the mini-hydropower and solar PV can serve complementary roles to improve EROI ratios. Also, of strong interest is that a mini-grid receiving at least 20% of annual generation from solar PV is competitive with coal-based grids (EROI=46) and considering that the EROI of coal is declining, this could provide further justification for renewable mini-grids from a net energy perspective. However, it is important to note the limitations of EROI and net energy, in that it does not consider environmental or climate externalities due to air pollution or CO_2 emissions. Policymakers should not use EROI estimates alone without considering environmental and social factors. The positive EROI values highlight the role mini-grids can play in meeting electricity needs to society while also providing net energy benefits to society. Lastly, the large EROI ratios for mini-grids highlight the potential for more distributed generation based designs to provide higher returns on energy investment than large scale centralized systems, likely because of the integrated and localized nature of distributed energy resources for electricity generation. Equation 2 describes the EROI for a mini-grid, that sums across any electricity generating or storing technology, *i* [Raugei et al., 2012].

$$EROI_{minigrid} = \sum_i \frac{\left(\frac{E_{lifetime\ output}}{\eta}\right)_i}{E_{materials_i} + E_{manufacturing_i} + E_{transport_i} + E_{install_i} + E_{end-of-life_i}}$$

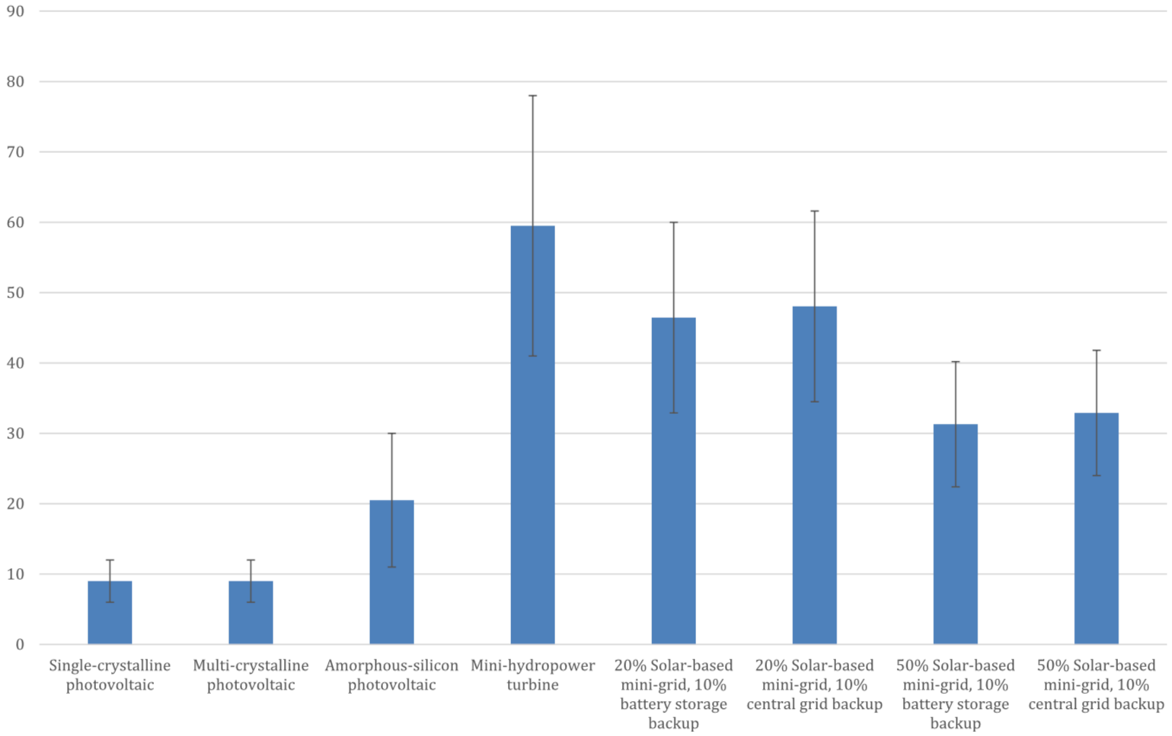

Figure 4. EROI of mini-hydropower and solar PV technologies in Thailand, by technology and varied mini-grid setups.

It seems that combining the solar PV and mini-hydropower into a hybrid system would decrease the EROI from using only mini-hydropower plants, however, if one adds some form of pumped storage to a solar PV plant, the overall system could benefit not only from an operations perspective, but EROI as lithium-ion ESOI is about 30 compared to pumped hydro storage which can reach up to 830. The life span of the mini-hydropower plant remains an important parameter that greatly changes the results of the reported EROI ratio as evidenced by Table 3. Therefore, this should be carefully considered going forward as more mini-hydropower plants in the real world reach maturation and are decommissioned in the future. Since this is a relatively new technology, there is not much experience to draw upon for estimated lifespan. The results suggest that mini-hydropower plants can become an energetically efficient investment that will provide society with strong net energy surpluses. When combined with other net energy positive technologies, including solar PV, environmental factors like limiting pollution from energy sources can be achieved and the diversity of the system allows for better environmental outcomes and dependence on renewable energy rather than non-renewables.

4. Discussion

Photovoltaics and mini-hydropower both have high energy return on energy investment ratios that serve as useful options to strive toward sustainable energy goals. It is useful to note that mini-hydropower can utilize more local resources during the construction phase and have a higher energy payback ratio than solar PV. However, the complementary nature of solar PV and mini-hydropower can alleviate issues of intermittency when used in the same system. During the summertime, mini-hydropower experiences lower levels of production due to fewer available water resources in northern Thailand. Recent advances in power islanding within mini-grids facilitates increased flexibility for solar PV and mini-hydropower to operate either with battery or grid-tied backup power in an integrated systems. The EROI of mini-hydropower and solar PV inform future sustainability studies of systems-scale diesel/biodiesel backed-up mini-grids. Additionally, the EROI of the existing mini-hydropower system competes closely with fossil fuels including coal and oil [Murphy & Hall, 2010]. EROI of fossil fuel resources continues to decline [Hu et al., 2013; Hall et al., 2014]. In the future, scale run-of-river hydropower plants could play a more significant role in our electricity systems as they transition from large, centralized designs to diverse, distributed sources that serve complementary roles. The addition of energy storage devices may decrease the net energy surplus from using hydro and solar dominated micro-grids. Using lithium-ion batteries for grid storage could potentially improve the energy return on invested of solar photovoltaics [Pellow et al., 2015].

Run-of-river hydropower plants could also enhance sustainability by constructing the systems using local resources. Both single-crystalline and amorphous-silicon solar PV panels often are manufactured in China and imported to Thailand. However, each energy technology utilizes locally available sunlight and water resources rather than imported fuel that would power a diesel or natural gas generator.

The overall potential for solar generation is larger than mini-hydropower in Thailand. However, mountainous regions in northern Thailand could greatly benefit by co-locating solar PV with mini-hydropower plants to achieve higher energy return on energy invested ratios and also to aid in load balancing by addressing intermittency issues, though these are not captured well in EROI calculations. Both mini-hydropower and solar PV embody fewer greenhouse gas emissions than alternative diesel and fossil fuel generators [Raadal, et al, 2011; Hsu et al., 2012]. Suitable locations for mini-hydropower should be explored further as they have very high energy payback ratios, emit few pollutants to the environment, and do not contain the same environmental externalities as mega dams. The use of mini-hydropower in northern Thailand along with solar PV will benefit energy security and environmental outcomes.

Future work may include an economic analysis to determine how the levelized cost of electricity generation between mini-hydropower at each site and solar PV compares with distributed diesel generation. The current estimated LCOE of mini-hydropower and solar PV At present the subsidy "adders" for mini-hydropower could provide up to seven years of support adding approximately \$0.02/kWh to all mini-hydropower installations selling electricity back to the Electricity Generating Authority of Thailand (EGAT).

Embodied energy and resulting environmental impacts can be reduced greatly if local materials and a local manufacturing supply chain is developed for both the mini-hydropower plants and the solar photovoltaic manufacturing as evidenced by the sensitivity of transportation energy in mini-hydropower EROI. Neither industry has strongly developed in Thailand, and therefore many of the materials that need to be imported contribute to lower than necessary energy returns on investment because of transportation energy required to assemble the mini-hydropower facilities [Suwanit & Gheewala, 2011]. Additionally, given the amount of steel, copper, and iron necessary to construct a mini-hydropower plant, the use of recycled materials can reduce the embodied energy. After the mini-hydropower plants are decommissioned there remain opportunities for materials and systems recycling. New manufacturing of distributed mini-hydropower plants could occur from decommissioned systems. Aluminium and silicon recovery from photovoltaic panels could create a type of industrial symbiosis that would benefit the regional economy, while improving energetic and environmental performance.

Energy return on investment (EROI) along with net energy analysis is a useful energy indicator for sustainability analysis and understanding society's distribution of resources. The application of life-cycle thinking to energy systems could better help design mini-grids that advance toward sustainable energy goals. However, EROI alone should not inform policy, it should be used alongside other decision-making criteria. The rapid decline in cost of mini-hydropower systems and solar photovoltaics enables new design thinking for mini-grids, especially in mountainous areas where transportation of diesel fuel is limited and expensive. In this case, mini-hydropower capacity and solar PV are both suitable technologies that will enable sustainable energy systems, if designed appropriately with environmental, economic, and societal considerations taken into account. Mini-grids are becoming critical tools as added flexibility for power systems and to build resilient systems that can operate in cases of limited electricity supply or grid malfunctions due to power outages and blackouts. This analysis sets the stage for further work into the EROI for other distributed energy resources and mini-grids as they become more ubiquitous as a way to meet power system capacity expansion. Further work would include more extensive analyses to determine optimal sizing of PV plants within mini-grids, quantify the role of energy storage with varying power and energy capacity ratios, and the economic design and deployment of mini-grid systems.

The EROI ratio for mini-hydropower systems is higher than solar PV; however, this does not preclude distinct advantages of solar PV to meet future electricity demand. Solar PV also yields a high EROI and can serve as an electricity option in areas that may not be suitable for mini-hydropower sites. Solar PV, when sited appropriately, can also reduce the need for added investment in transmission systems and could defer distribution component upgrades by selectively providing voltage support or reactive power. Solar PV can reduce the net energy demand when coordinated with the utility to ensure proper grid integration. We highlight that a suite of low-carbon technologies can also provide financially and energetically competitive options for a mini-grid system. Diesel backup mini-grids are not the only technology option available, and mountainous regions could take advantage of locally available resources first before resorting to the use of diesel for backup. The positive EROI ratios indicate societal benefits to utilizing mini-hydropower and solar PV systems in mini-grids as they can improve the quality of energy by meeting electricity supply needs. Another upshot of the calculated EROI ratios is that they may be increasing with technological advances and improvements in performance efficiency and product lifetimes. The technological improvements in solar PV and mini-hydropower have improved the EROI ratios since earlier studies in the late 1990's and early 2000's, renewing interest in distributed energy resources, and improving the energetic balance for these emerging technologies.

Since mini-hydropower can counter power outages and help balance loads during periods of peak demand, this is a highly sought after source of electricity for rural mountainous Thailand, with spotty electricity provided by the PEA. Coupled with solar PV, both technologies will provide stability to the electricity grid while serving as net-energetically positive investments in primary energy and resources. Attention toward mini-hydropower in Thailand should grow in the future due to policy support, appropriate geologic features, and the ability to obtain a high net energy payback ratio. The feed-in tariff support toward mini-hydropower is not currently developed to its full potential. Also, the construction of more mini-hydropower plants in Thailand can provide the necessary infrastructural support that accommodates grid-connected or mini-grid-connected solar PV. The expected future decline in cost of solar PV combined with the increased demand for renewable technologies will likely spur development of mini-hydropower and solar PV systems to meet sustainability and energy goals.

5. Conclusions

First, we report the EROI of mini-hydropower systems in Thailand using real data available from five different mini-hydropower sites, that can range from 41-284, depending on transportation energy requirements and assumptions of lifespan. Second, we synthesize literature-based estimates and simulate EROI for three solar PV technologies and review different battery storage options for a mini-grid. We then use scenarios of annual generation for solar PV and mini-hydropower plants designed in a mini-grid setup to evaluate the EROI for mini-grids, which we find to be net positive and sometimes more competitive than fossil-based large scale centralized grids. This hinges on the fact mini-hydropower has a high EROI compared to many fossil-fuel based generators. Solar PV technologies can range from 6-12 in EROI and amorphous-silicon PV can be from 11-30. At the same time, EROI of mini-hydropower can be greater than 41 in to the 100's and other mini-grid setups based on mini-hydro and solar PV range between 21-62. These analyses do not consider social or environmental externalities, yet provide a window into the potential societal benefits of distributed mini-grid electricity generation. The flexibility of mini-grids to meet underserved energy needs and the dramatic cost declines of mini-hydropower and solar PV technologies is driving a change toward more distributed energy systems. Our findings suggest these systems can provide net energy benefits to society, as mini-hydropower does have a high EROI and further these systems already challenge fossil-fuel based grid EROIs.

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Conclusion

The cases range from a national scale electricity options study in Kosovo to the innovations in energy storage that could enable a global clean energy transition, and the small-scale cases of solar, mini-hydro, and storage mini-grids that may alter the investment paradigm. The analytical tools utilize a systems approach and compare unique metrics that can improve electricity planning models by incorporating underutilized information related to health impacts and technological innovation.

The models developed in the dissertation have altered the discussion and investment plans surrounding the construction of a new coal-fired power plant in Kosovo. As of May 2018, it remains unlikely the World Bank will provide a loan guarantee for a new coal-fired power plant in Kosovo.

A prosperous Kosovo will need jobs for a modern economy, as well as a low-cost, affordable, and reliable electricity supply. Chapter 1 demonstrates that an integrated package of investments in energy efficiency and renewable electricity including solar, wind, and small-scale sustainable hydropower – could provide the same amount of electricity as a new coal-fired power plant at a lower cost. More importantly, an integrated energy system will create more jobs and reduce the financial risk across a large number of projects. We also note that the five-year lag time before a plant begins operations will significantly set back Kosovo by forcing it to rely on dirty, lignite coal-powered electricity from the Kosovo A and B power plants.

The five-year construction schedule will also significantly disrupt public health. The lack of fabric filters to manage the emissions of PM10 and PM2.5, dangerous particulate matter, from existing boilers makes Pristina one of the worst places to live in all Europe from an air pollution and public health perspective. Chapter 2 shows that lignite coal burned in Kosovo's power plants contains elevated levels of arsenic, chromium, and nickel – toxic metals that are not safe for humans that worsen the air pollution crisis.

On the contrary, solar and wind projects have significantly lower startup costs and can deploy within months, rather than years. Improvements in battery storage technologies detailed in Chapter 3 have enabled solar and wind projects to operate more like conventional baseload power plants, simplifying grid integration. The 100 MW lithium-ion battery facility in South Australia was recently completed in less than 100 days. Planners have spent 13 years debating the future of the new Kosovo C power plant.

Waiting to build a coal-fired power plant, instead of deploying energy efficiency projects and renewable energy today, will also exacerbate energy security issues. In the short-term, the lag will force Kosovo to import more electricity from Serbia when Kosovo A and B cannot run. This is a security issue, since Kosovo already has problems maintaining domestic coal reserves, and Serbia could control the price of electricity imports. As just one recent example, since January 2018, a dispute with Belgrade over balancing Kosovo's lost load has altered frequency levels on the European power grid, causing electric clocks to lag behind, with losses totaling more than 113 GWh.

The power plant will also prevent Kosovo from complying with EU air pollution directives. Future EU accession hinges on such compliance. Even if Kosovo builds the power plant, Serbia maintains control over the water resources of Gazivoda Lake – the water cooling source for Kosovo B -- and Serbia could halt Kosovo's water supply on a whim. On the other hand, solar, wind, and storage provide Kosovo with greater control and sovereignty over its energy future.

Chapter 4 concludes with an analysis of the energy return on investment for a mini-grid in Thailand. The innovative set-up and design of new energy technologies in smaller, decentralized networks offers new opportunities to view power systems. In the future, we may expect mini-grids to offer a glimpse of the alternatives to large-scale infrastructure projects and their increasing competitiveness, energy, environmentally, and cost-wise, to enable better resource management and systems integration for a clean energy transition.

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