

# Energy Storage and Clean Energy Transitions

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## Abstract

The development of energy storage technologies creates opportunities for clean energy transitions in the transportation and electricity sectors. These technologies receive public and private support, yet their effective deployment faces various challenges that can potentially hinder climate goals, particularly in the electricity sector. We examine economic and technical challenges within a well-known induced innovation model where we introduce a new energy storage subsidy. At current levels of substitution between clean and conventional technologies, our results highlight the importance of temporarily subsidizing storage technologies to ease the substitution between clean and conventional technologies. Our discussion aims at improving the understanding of energy storage deployment that has the potential to accelerate clean energy transitions.

**Keywords:** Directed technical change; energy storage; clean energy transitions

**JEL Classification Codes:** O3, O4, O5, Q2, Q3, Q4, Q5

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## 17 Introduction

18 Global clean energy transitions in the transportation and power sectors hinge upon the  
19 deployment of new and improved technologies. In transportation, electric vehicles pow-  
20 ered by batteries emerge as a critical technology to decarbonize road transportation. The  
21 electricity sector, however, presents a more intricate landscape for clean energy technology  
22 deployment. On the one hand, energy storage is a pivotal solution to the intermittency  
23 problem of renewable resources like wind and solar, which can help their expansion. Yet,  
24 energy storage introduces flexibility into the energy system, enhancing the efficiency of  
25 conventional power plants. By enabling electricity production at a consistent rate, energy  
26 storage minimizes ramping costs and opens new arbitrage possibilities. Therefore, energy  
27 storage has the potential to change the technical transition in the energy sector beyond its  
28 ability to promote the use of intermittent renewable energy.

29 We center our attention on the incentives driving the innovation and deployment of  
30 storage technologies, and their role in the transition to cleaner energy. Induced innova-  
31 tion in the energy sector, in combination with temporary policies like carbon taxes and  
32 research subsidies, can direct innovation towards clean inputs to achieve sustainable eco-  
33 nomic growth (Acemoglu et al., 2012). In their model, the optimal policy involves carbon  
34 taxes and research subsidies to the clean sector. This well-established economic model  
35 provides valuable insights into the mechanisms that can propel a transition toward cleaner  
36 energy and serves as a theoretical foundation for subsequent empirical analysis. For exam-  
37 ple, building on this framework, Lazkano et al. (2017), using a firm-level dataset of patents,  
38 were among the first to empirically analyze the significance of electricity storage in the en-  
39 ergy sector. Similarly, Fabrizio et al. (2017) use international panel data to examine the  
40 impact of demand- and supply-pushed policies on energy storage innovation. While these  
41 examples focus on empirical evidence, our focus is on the challenges inherent in achieving  
42 these energy transitions within this theoretical framework, particularly given the existing  
43 technological level and costs of energy storage.

44 Governments around the world have implemented policies directed at expanding short-  
45 run and long-run storage capacity, and at mobile and stationary sources. For example,  
46 the European Commission approved an Important Project of Common European Interest  
47 (IPCEI) in 2019, specifically aimed at supporting research and innovation in batteries.<sup>1</sup> In

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<sup>1</sup>This project is jointly notified by Belgium, Finland, France, Germany, Italy, Poland and Swe-  
den, focusing on four areas: raw and advanced materials, cells and modules, battery systems,

48 the United States, the Department of Energy (DOE) initiated the Grid Storage Launch-  
49 pad (GSL) project in 2021, allocating USD 75 million for the facility located at the Pacific  
50 Northwest National Laboratory (PNNL). This facility serves as a collaborative space for re-  
51 searchers and industry experts, fostering the acceleration of energy storage innovation and  
52 bolstering clean energy adaptation and grid resilience.<sup>2</sup> Despite the considerable potential  
53 for stationary storage solutions, the current deployment of storage technologies primarily  
54 revolves around batteries for electric vehicles (EV). For instance, policies directed at reduc-  
55 ing the cost of purchasing and owning EVs started in 1990 in Norway, in 2008 in the U.S.,  
56 and in 2014 in China (IEA, 2021a). By 2023, fiscal incentives helped EV sales in many  
57 countries including Canada, China, European Union, India, Japan, and the United States.<sup>3</sup>  
58 These instances highlight the worldwide efforts to advancing energy storage through public  
59 funding.

60 Our aim is to understand the role of government subsidies to enhance storage deploy-  
61 ment. To achieve this, we introduce a storage research subsidy in the model of Acemoglu  
62 et al. (2012). The original directed technical model of Acemoglu et al. (2012) describes  
63 that an economy must satisfy the following two conditions to avoid environmental disaster:  
64 (1) clean and dirty production inputs must maintain a sufficiently high elasticity of substi-  
65 tution, and (2) the adoption of a temporary yet substantial subsidy to clean research and  
66 a long-term carbon tax. In our analysis below, we introduce a proportional profit subsidy  
67 to energy storage in the expected profit from undertaking research in clean and dirty sec-  
68 tors. As energy storage complements the intermittent renewable energy and improves the  
69 efficiency of conventional power plants, storage technologies, as well as policies promoting  
70 its innovation such as a research subsidy, will contribute to both clean and dirty sectors,  
71 regardless of whether they are based on renewable or fossil fuel energy sources.<sup>4</sup> Therefore,

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and repurposing, recycling and refining. See “State aid: Commission approves €3.2 billion public support by seven Member States for a pan-European research and innovation project in all segments of the battery value chain on European Commission page: <https://www.energy.gov/articles/doe-launches-design-construction-75-million-grid-energy-storage-research-facility>.

<sup>2</sup>See “DOE Launches Design & Construction of \$75 Million Grid Energy Storage Research Facility” on Department of Energy page: <https://www.energy.gov/articles/doe-launches-design-construction-75-million-grid-energy-storage-research-facility>.

<sup>3</sup>In addition to these large economies, smaller countries also provide public support for EVs. For example, in 2023 the Estonian Ministry of Economy announced a substantial commitment of EUR 7.8 million in subsidies for renewable energy storage. Under this initiative, beneficiaries can draw up to EUR 360,000/MWh of electricity storage. Also, the Thai government allocated THB 24 billion to subsidize the production of battery cells for EVs to meet Thailand’s national target of 30% of the total electric car production by 2030.

<sup>4</sup>For example, Feng (2024) shows that out of 9,970 storage patent applications from 2,194 firms in the electricity sector, the majority, over 90%, were filed by mixed firms innovating in both generation

72 unlike the clean sector subsidy in the original model, our storage subsidy benefits both  
 73 sectors.

## 74 Directed technical change with a storage subsidy

75 In this section, we briefly summarize the well-known directed technical change model of  
 76 Acemoglu et al. (2012) before presenting our model that includes a storage subsidy. Firms  
 77 produce a unique final good competitively using inputs from two sectors, “dirty” and  
 78 “clean.” The ease of substitution between the clean and dirty production inputs is  $\epsilon$ . In  
 79 each sector, firms use labor ( $L_j$ ,  $j = c, d$ , clean and dirty) and source-specific machines  
 80 to produce the input of the final good, where the technology level affects the production  
 81 efficiency ( $A_j$ ). Firms invest in technological innovation at the beginning of the period,  
 82 and at the end of the period they produce with newly improved technologies. Scientists  
 83 choose whether to direct their research to dirty or clean technology. In the decentralized  
 84 equilibrium without any policy intervention, innovation in the energy sector is directed  
 85 by energy prices ( $p_j$ ), previous technological levels ( $A_{jt-1}$ ), and market sizes ( $\eta_j$ ). In  
 86 equilibrium, the relative benefit from undertaking research in clean to dirty sector is given  
 87 by equation 1:

$$\frac{\Pi_{ct}}{\Pi_{dt}} = \frac{\eta_c}{\eta_d} \left( \frac{p_{ct}}{p_{dt}} \right)^{\frac{1}{1-\alpha}} \frac{L_{ct} A_{ct-1}}{L_{dt} A_{dt-1}}, \quad (1)$$

88 where  $\Pi_{jt}$  represents the expected profit for a scientist engaged in research in sector  $j$  at  
 89 time  $t$ . Acemoglu et al. (2012) show that the optimal policy to avoid a natural disaster  
 90 involves a carbon tax  $\tau_t$  and a subsidy to the clean sector  $q_t$ . Thus, the relative benefit in  
 91 equation 1 becomes:

$$\frac{\Pi_{ct}}{\Pi_{dt}} = (1 + q_t) \frac{\eta_c}{\eta_d} \left( \frac{1 + \gamma \eta_c s_{ct}}{1 + \gamma \eta_d s_{dt}} \right)^{-\varphi-1} (1 + \tau_t)^\epsilon \left( \frac{A_{ct-1}}{A_{dt-1}} \right)^{-\varphi}. \quad (2)$$

92 In addition to the policy interventions outlined by Acemoglu et al. (2012), we incorporate  
 93 a research subsidy for energy storage,  $q_t^s$ . Unlike the clean sector subsidy, this storage  
 94 subsidy contributes to both sectors. Therefore, given a carbon tax  $\tau_t$ , a subsidy to the  
 95 clean sector  $q_t$ , and a subsidy to energy storage  $q_t^s$ , the innovation decision is now driven

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and storage technologies. Notably, 79.89% of these mixed firms conduct research on both renewable and fossil-fuel generation technologies alongside storage innovation.

96 by:

$$\frac{\Pi_{ct}}{\Pi_{dt}} = \left( \frac{1 + q_t + q_t^s}{1 + q_t^s} \right) \frac{\eta_c}{\eta_d} \left( \frac{1 + \gamma \eta_c s_{ct}}{1 + \gamma \eta_d s_{dt}} \right)^{-\varphi-1} (1 + \tau_t)^\epsilon \left( \frac{A_{ct-1}}{A_{dt-1}} \right)^{-\varphi}. \quad (3)$$

97 Next, we use a quantitative example to highlight the effect of a storage subsidy for different  
 98 values of the elasticity of substitution between clean and dirty inputs ( $\epsilon = 1.5$ ,  $\epsilon = 3$ ,  
 99  $\epsilon = 10$ ), and three different levels for our storage subsidy:  $q_t^s = 0.5q_t$ ,  $q_t$ , and  $1.5q_t$ . For  
 100 consistency, the parameter values are as in Acemoglu et al. (2012):  $\eta_j = 0.02$ ,  $\gamma = 1$ ,  
 101  $\alpha = 1/3$ . The optimal policies depend on different values of the elasticity of substitution  
 102 between clean and dirty inputs  $\epsilon$ .

103 A substantial body of existing literature provides estimates of the elasticity of substi-  
 104 tution between clean and dirty energy inputs. For example, Goulder and Schneider (1999)  
 105 find a value of 0.9. Using a steady-state assumption, Lanzi and Sue Wing (2010) estimate a  
 106 value of 1.6 in the energy sector. Popp (2004) find the same value for the elasticity of sub-  
 107 stitution between fossil fuels and nonfossil fuels in the modified DICE model. Papageorgiou  
 108 et al. (2017) estimate nested CES specifications using nonlinear estimation, which imply a  
 109 value of 1.8 in the electricity-generating sector and a value of 3 in non-energy industries.  
 110 While the estimates vary with time, geography, and industry, the collective findings from  
 111 these studies suggest that the power sector is still close to a low substitution scenario. In  
 112 contrast, the transportation sector exhibits a higher elasticity of substitution (Xing et al.,  
 113 2021; Leard and Wu, 2023; Stöckl and Zerrahn, 2023). Acemoglu et al. (2012) consider high  
 114 values of the elasticity of substitution,  $\epsilon = 3$  and  $\epsilon = 10$ , representing a world in which  
 115 clean and dirty inputs are easily substitutable. Based empirical estimates, we consider  
 116  $\epsilon = 1.5$  in addition to the higher values,  $\epsilon = 3$  and  $\epsilon = 10$ .

117 In scenarios where the elasticity of substitution is higher, our quantitative example  
 118 shows that implementing a storage subsidy is unnecessary. This is expected given that  
 119 clean inputs can readily substitute dirty inputs under such circumstances, and a natural  
 120 disaster is avoided. However, when the elasticity of substitution is closer to empirical  
 121 evidence,  $\epsilon = 1.5$ , the storage subsidy impacts the optimal allocation. Specifically, we find  
 122 that introducing a higher storage subsidy can significantly shorten the duration of a clean  
 123 innovation subsidy as well as postpone its timing. Thus, our results show the importance  
 124 of targeting storage technologies when the substitution between clean and dirty inputs is  
 125 low. Once the ease of substitution improves, the role of a storage subsidy subsides and a  
 126 clean technology subsidy becomes important.

## 127 Discussion

128 Energy storage has the potential to ease the substitution between clean and dirty inputs.  
129 However, the existing landscape of storage technologies poses limitations due to their high  
130 costs and restricted expansion. In the electricity sector, the most widely deployed tech-  
131 nology is pumped-storage hydropower followed by grid-scale batteries, while lithium-ion  
132 batteries are commonly used in electric vehicles within the transportation sector. The ex-  
133 pansion of pumped-storage hydropower is geographically limited, whereas the production  
134 of batteries used in solar photovoltaic plants, wind farms and electric vehicles relies on  
135 nonrenewable minerals like cobalt, nickel, and lithium.<sup>5</sup> Thus, none of these technologies  
136 are mature enough for extensive deployment to achieve high elasticities of substitution  
137 between clean inputs like wind and solar and dirty inputs like coal and natural gas.

138 Another challenge for energy storage deployment relates to its production. The produc-  
139 tion of batteries relies on non-renewable minerals and so these critical minerals have gained  
140 heightened attention on both policy and business agendas in recent years. To illustrate, an  
141 electric car consumes six times the mineral inputs of a conventional car (IEA, 2023). The  
142 global surge in renewable energy and EV adoption has resulted in an increased demand  
143 for minerals. In 2022, demand for lithium-ion batteries from EVs rose by around 65%,  
144 reaching 550 GWh, while the battery energy storage market nearly doubled to 80 GWh,  
145 which has been one of the largest annual increases ever witnessed in these sectors.

146 Innovation in new technologies that rely less on critical minerals presents a potential  
147 solution, but unfortunately, these technologies are currently cost ineffective for large scale  
148 expansion. For example, one such technology is sodium-ion batteries, which are free of  
149 lithium, and they rely on sodium that can be found anywhere. The first sodium-ion  
150 battery car (BYD Seagull) was introduced in April 2023 and mass production of sodium-  
151 ion batteries expected for 2023. As a proxy of innovation, the cumulative count for post-  
152 lithium-ion battery patents approaches nearly 10,000 by 2023. Indeed, the global patent  
153 race in the last decade underscores the dominance of patents for sodium-ion batteries. This  
154 example shows how innovation has the potential to offer alternatives to batteries dependent  
155 on non-renewable materials like lithium. Unfortunately, currently, storage technologies that

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<sup>5</sup>IEA (2021b) states that “*the types of mineral resources used vary by technology. Lithium, nickel, cobalt, manganese and graphite are crucial to battery performance, longevity and energy density. Rare earth elements are essential for permanent magnets that are vital for wind turbines and EV motors. Electricity networks need a huge amount of copper and aluminium, with copper being a cornerstone for all electricity-related technologies.*”

156 are independent of critical materials are unavailable at a cost effective and large scale.

## 157 **Conclusions and policy implications**

158 As technical improvements enable a net-zero future, it is crucial to fully understand the role  
159 of energy storage, particularly its innovation, existing limitations, large-scale availability,  
160 and its potential for clean energy transitions. We model the role of an energy storage  
161 subsidy in induced innovation in the energy sector. Specifically, we introduce a research  
162 subsidy for energy storage that spans both clean and dirty sectors in the model developed  
163 by Acemoglu et al. (2012). Our quantitative example shows that a storage subsidy changes  
164 the optimal subsidy to clean innovation, particularly when the elasticity of substitution  
165 between two sectors is low. Furthermore, different levels of storage subsidies postpone  
166 the timing of the clean innovation subsidy's adoption, shorten its duration, or lower its  
167 optimal level. Therefore, energy storage might play a more important role in clean energy  
168 transitions by improving the substitution between inputs than encouraging clean innovation  
169 directly. This is the case because solving the intermittency problem will increase the ability  
170 of renewable technologies to substitute conventional energy in the power sector.

171 We focus on the current level of substitution between clean and dirty inputs, and  
172 the role of storage subsidies on clean energy transitions. While the transportation sector  
173 may experience a relatively easier substitution, the power generation sector faces a more  
174 challenging substitution dynamic. This is crucial to understand the feasibility of clean  
175 energy transitions as high values of substitution play an important role in determining  
176 optimal policy formulations. We emphasize the importance of directing public efforts  
177 at improving the substitution between clean and dirty inputs, particularly in the power  
178 sector. Energy storage technologies, such as those for solar power and wind power, emerge  
179 as crucial elements in this pursuit. A prominent illustration of the positive impact of energy  
180 storage is the Hornsdale Power Reserve in South Australia. This large-scale energy storage  
181 facility, featuring Tesla's lithium-ion batteries, has been instrumental in stabilizing the  
182 power grid and supporting the integration of renewable energy, particularly solar power.  
183 The success of this project has garnered international attention and demonstrated the  
184 potential of energy storage to enhance the reliability and efficiency of solar power systems.<sup>6</sup>  
185 Thus, as we navigate towards cleaner energy futures, policymakers should strategically

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<sup>6</sup>See Hornsdale Power Reserve's official website at <https://hornsdalepowerreserve.com.au>.

186 formulate policies that foster advancements in energy storage technologies and enhance  
187 substitution dynamics in power generation.

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## 220 Appendix

221 Equations 1 and 2 directly follow from Acemoglu et al. 2012 equation 17 and A17, respec-  
 222 tively, and they are derived using the same mathematical framework outlined in their work,  
 223 specifically Appendix I A and D. From there, the relative expected profit of innovation in  
 224 clean sector is:

$$\frac{\Pi_{ct}}{\Pi_{dt}} = (1 + q_t) \frac{\eta_c}{\eta_d} \left( \frac{1 + \gamma \eta_c s_{ct}}{1 + \gamma \eta_d s_{dt}} \right)^{-\varphi-1} (1 + \tau_t)^\epsilon \left( \frac{A_{ct-1}}{A_{dt-1}} \right)^{-\varphi}.$$

225 The tax  $\tau_t$  and the subsidy  $q_t$  show the proposition that the socially optimal allocation  
 226 can be implemented with this scenario. Likewise, we introduce a tax  $\tau_t$  and two subsidies  
 227  $q_t$  and  $q_t^s$  to correct the environmental and knowledge externality of clean and storage  
 228 technologies.

229 In the optimal allocation of resources, scientists will be allocated towards the sector  
 230 with the higher social gain from innovation. The social planner will allocate scientists to  
 231 the clean sector to increase the productivity and to promote storage, while it will direct  
 232 scientists to the dirty sector to promote storage. The social planner can implement this  
 233 optimal allocation through a subsidy  $q_t$  and  $q_t^s$  to clean research, and  $q_t^s$  to dirty research.  
 234 Therefore, for given subsidies  $q_t$  and  $q_t^s$ , the ratio of expected profits from innovation can  
 235 be written as:

$$\frac{\Pi_{ct}}{\Pi_{dt}} = \left( \frac{1 + q_t + q_t^s}{1 + q_t^s} \right) \frac{\eta_c}{\eta_d} \left( \frac{1 + \gamma \eta_c s_{ct}}{1 + \gamma \eta_d s_{dt}} \right)^{-\varphi-1} (1 + \tau_t)^\epsilon \left( \frac{A_{ct-1}}{A_{dt-1}} \right)^{-\varphi}.$$