# Supplementary Appendix

*Additional Material for “Engines of Power”*

# Extended citations for Figure 2: Military electrification GPT Tree

Electric lighting: searchlights (Rey 1917, 1); the *HMS Inflexible* was the first warship to adopt electric lighting in 1881 (Smith 2013, 229-231); warships with searchlights and electric lighting in Russo-Japanese war (Jukes 2002, 90).

Electric power: first electric firing of guns on battleships (Hezlet 1975, 15); the first electricity-powered submarine references the *Holland*, designed in 1896 with a battery-powered electric motor (Coté Jr. 2003, 5). One-third of British dreadnoughts had adopted “director firing” (electric control of all ship guns) before WWI (Hezlet 1975)

Electric communications: widespread use of electric telegraph in US civil war (Parkhurst 1892, 317); first fleet equipped with wireless communications in 1900 (Lautenschlager 1983, 16)

# Extended citations for Table 1: Delayed impact of electrical military innovations

Wireless telegraphy: British fleet equipped with wireless telegraph (Lautenschlager 1983, 16); Russo-Japanese War as first application of wireless in war (Headrick 1991, 124); British Royal Navy has “patchy global network” that supported radio communication (Hezlet 1975, 78); planes equipped with radio at end of WWI (Back and Thompson 1988); Germany equips air force with complete set of radio equipment (Back and Thompson 1988).

Electric firing of guns: British navy introduces electric firing ((Hezlet 1975, 15); Half of British fleet had director firing by 1914 (Hezlet 1975); GE develops electric-powered miniguns (Historical Firearms, n.d.); U.S. procured 10,000 miniguns during Vietnam War (Gourley 2019).

# Full justification for submarines as non-GMT

*GMT Features 1 and 2: Broad Impact Pathway and Productivity Spillovers*

The discovery of electromagnetic waves influenced military affairs through empowering a broad array of military applications, whereas submarines influenced military affairs largely through the narrow pathway of a weapons platform. The technology tree for advances in underwater submersion technology was much narrower than the one for electricity. The main use of submarines was as a weapon system. The only other substantial application was in reconnaissance. In WWI, the British did use submarines as important supplements to radio intelligence, as the development of new wireless transmitters allowed patrol submarines to relay information back to the larger fleet.[[1]](#footnote-1)

An especially compelling illustration of the ways that electricity had a much broader impact than submarines is the fact that the causal impact between these technologies was unidirectional. Advances in electricity empowered submarine applications, whereas advances in submarine technology did not empower electrical applications. For instance, diesel-electric systems were crucial to boosting submarine capabilities. When submerged, submarines were powered by electric batteries and motors; when surfaced, they were powered by diesel engines.[[2]](#footnote-2)

In some respects, it was difficult to predict the net strategic implications of submarines on naval warfare. Before the outbreak of WWI, no major naval power foresaw that commerce raiding would become the main use case for submarines.[[3]](#footnote-3) As Brodie writes, “It would have been impossible to predict in advance the effects of science on naval strategy during WWI. No one foresaw that the submarine would be the colossal threat it proved to be.”[[4]](#footnote-4)

Overall, however, it was easier to anticipate the overall effect of the submarine on warfare than it was for electricity. The strategic implications of submarines, though somewhat unpredictable, were sourced from a relatively stable and bounded application of submarines: “hit and hide” attacks for naval attrition. It was relatively easy to foresee this application even if there was some uncertainty regarding the magnitude of the effect of “hit and hide” attacks as well as how “hit and hide” attacks fit into broader naval strategy.

Moreover, there were few significant breakthroughs in new submarine capabilities for many decades after their introduction into military affairs. In contrast with GPTs, which experience continual improvement fueled by an entire research field, the range and speed of submarines stayed relatively constant in the interwar period, with marginal improvements in operating depth and better armament.[[5]](#footnote-5) As Rossler points out, “[U]ntil WWII, submarine development required only reliable and powerful diesel engines, welding of metals, and efficient designs.”[[6]](#footnote-6) Even in WWII, the German’s principal U-boat design was only a slight upgrade on their UB-111 boats launched in 1917.[[7]](#footnote-7)

Given this narrow pathway of direct military impact, it is no surprise that submarine technology had limited effects on industrial productivity. While more recent advances in submarine technology offer prospects for some spillovers in radar and ocean imaging capabilities, underwater submersion technology in the second half of the century had very few civilian applications. Thus, the properties of submarine technologies deviated from the first two features of a GMT.

*GMT Feature 3: Time Lag*

In addition, there was a relatively short gestation period before the submarine made a significant impact on military effectiveness. Of course, clarifying the start of the gestation period is an essential part of this assessment. The first functional submarine can be traced back to 1776, and advances in underwater propulsion, suitable weapon systems, and air supply systems for underwater crew saw an uptick in the 1860s.[[8]](#footnote-8) But we date the emergence of submarine technology to the late 19th century, a period characterized by intensive submarine development.

In 1899, the French launched the *Narval*, which was propelled on the surface by a steam engine and by electric motors when submerged. In 1886, two Englishmen built the *Nautilus*, which operated by all-electric propulsion. Ultimately, a diesel-electric system came to fuel the 20th century submarine. This emerged early on in the 20th century (see Figure X below). Surface motive power was the critical technological bottleneck for submarines. As Nimitz writes:

“No matter how well the hull be designed and arranged; no matter how efficient the electrical equipment or the torpedos, the submarine will be a failure if her main motive power is not absolutely reliable. Indeed, some builders have discovered to their sorrow, that the submarine should be built around a reliable engine, instead of designing an engine to suit the hull.”[[9]](#footnote-9)

Within a short timeframe, navies adopted submarine technology. WWI, the first war that involved the use of submarine technology, is often dubbed *The Submarine War.*[[10]](#footnote-10) In 1913, before the outbreak of war, the U.S. had 33 diesel-electric submarines, France had 58, Great Britain had 77, Germany had 29, Russia had 16, and Japan had 1.[[11]](#footnote-11) According to periodizations of naval technology, the period from 1906 to 1946 is often the one that scholars identify when the impact of submarines was felt most in terms of giving an actor with the technology a significant military advantage.[[12]](#footnote-12)

# Details on Middlesex Tribunal Case File Analysis

To assess our theory that industrial dependency is more pronounced for GPTs than other technologies, including dual-use sectors like chemicals and steel, we examined military service appeal case files from the Middlesex tribunal from 1916-1918. These records included over 8,000 appeals against conscription into army service on grounds of ill-health, conscientious objection, exempted occupations, and that “it is expedient in the national interests that the man should, instead of being employed in military service, be engaged in other work which he wishes to be engaged.” (Military Service Act 1916, ch. 104).

We searched through these records by occupation. There were 58 cases that contained the word “electrical” in the occupation category. There were only 8 cases that included the word “chemical” in the occupation category. There were only 7 cases that included the word “steel” in the occupation category. No cases included the word “submarine” in the occupation category. We thank the Friends of the National Archives and the Federation of Family History Societies for making these records available.

Regarding the exempted occupations, the UK government released a list of occupations certified by Government Departments for exemption in 1917. One of the eight “general reservations” that applied to all the industries in the country was for electricians responsible for operating and maintaining motors in factories.[[13]](#footnote-13)

Contemporary trade journals detailed disputes in these tribunals between electrical companies and military representatives over scarce talent. For instance, at one appeal in the Weymouth tribunal where Brooking & Co. was trying to hold on to its electrical engineers, the military representative stated that “the military were in urgent need of electricians.”[[14]](#footnote-14)

# Additional References for Supplementary Appendix

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1. Hezlet 1975, 133 [↑](#footnote-ref-1)
2. Hezlet 1975. [↑](#footnote-ref-2)
3. Coté Jr. 2003, 6; Lautenschlager 1987. [↑](#footnote-ref-3)
4. Brodie and Brodie 1973, 187. [↑](#footnote-ref-4)
5. Lautenschlager 1987, 123. After WWII, the arming of submarines with nuclear warheads represented a significant leap in their capabilities. For more on the post-WWII evolution of submarines, see Coté Jr. 2003. [↑](#footnote-ref-5)
6. Rössler 1981, 50. Cited in Gilli and Gilli 2019 (156n88). Gilli and Gilli (2019, 152) do make the point that modern submarines have substantially increased in complexity and have experienced improvements in speed and collapse depth. [↑](#footnote-ref-6)
7. Polmar and Moore 2004, 2. [↑](#footnote-ref-7)
8. Lautenschlager 1987, 102. Lautenschlager argues that the first submarine with all the basic technology to function as a naval weapon system was introduced in 1910. [↑](#footnote-ref-8)
9. Nimitz 1916, 488. [↑](#footnote-ref-9)
10. Skjong et al. 2015. It could be the case that war was the motivating shock for diffusion for both cases. [↑](#footnote-ref-10)
11. Crisher and Souva 2014. [↑](#footnote-ref-11)
12. Crisher and Souva 2014; Modelski and Thompson 1996. [↑](#footnote-ref-12)
13. National Archives Catalogue reference: MH 47/142/2. [↑](#footnote-ref-13)
14. *Electrical Review*, August 3, 1917, 106. [↑](#footnote-ref-14)