

Review

Strategic Investment in Open Hardware for National Security

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Abstract: Free and open source hardware (FOSH) development has been shown to increase innovation and reduce economic costs. This article reviews the opportunity to use FOSH like a sanction to undercut imports and exports from a target criminal country. A formal methodology is presented for selecting strategic national investments in FOSH development to improve both national security and global safety. In this methodology, first the target country that is threatening national security or safety is identified. Next, the top imports from the target country as well as potentially other importing countries (allies) are quantified. Hardware is identified that could undercut imports/exports from the target country. Finally, methods to support the FOSH development are enumerated to support production in a commons-based peer production strategy. To demonstrate how this theoretical method works in practice it is applied as a case study to the current criminal military aggressor nation, who is also a fossil fuel exporter. The results show there are numerous existing FOSH and opportunities to develop new FOSH for energy conservation and renewable energy to reduce fossil fuel energy demand. Widespread deployment would reduce the concomitant pollution, human health impacts, and environmental desecration as well as cut financing of military operations.

Keywords: energy policy; energy conservation; climate change; global safety; open hardware; open source; photovoltaic; renewable energy; solar energy; national security

1. Introduction

Free and open source software (FOSS) is released under a license that allows anyone to use, copy, study, and change it, and the source code is openly shared so that people are encouraged to voluntarily improve the design in exchange for requiring adaptations to be re-shared with the same license [1]. This gift economy [2] results in rapid innovation [3,4] and using FOSS licenses has been widely [5] and repeatedly [6] successful [7]. FOSS has become a dominant form of technical development in the software industry and now 90% of cloud servers [8] run open source operating systems (this includes most internet companies such as Facebook, Twitter, Yahoo, Google and Amazon) as do 90% of the Fortune Global 500 (e.g. including less-tech focused companies like Wal-Mart and McDonalds) [9]. Similarly, 100% of supercomputers [10], over 84% of the global smartphone market [11] and more than 80% of the IOT (internet of things) market [12] also use FOSS.

The same open source development paradigm [13,14] has started to democratize [15] manufacturing of physical products [16]. This is known as free and open source hardware (FOSH). The Open Source Hardware Association defines open source hardware [17] as:

Hardware whose design is made publicly available so that anyone can study, modify, distribute, make, and sell the design or hardware based on that design. The hardware's source, the design from which it is made, is available in the preferred format for making modifications to it. Ideally, open source hardware uses readily-available components and materials, standard processes, open infrastructure, unrestricted content, and open-source design tools to maximize the ability of individuals to make and use hardware.

Open source hardware gives people the freedom to control their technology while sharing knowledge and encouraging commerce through the open exchange of designs.

Open hardware uses viral licenses (e.g. CERN [18]) that demands if users make modifications, they must share their improvements with the global community [19]. FOSH is demonstrating rapid innovation [20-22] and is roughly 15 years behind FOSS in terms of technical development [23].

One of the core strengths of FOSH is the ability to replicate the hardware from digital designs [24,25] that themselves can be customized [26] with FOSS [27]. Digital fabrication of open source designs enables wealth growth [28-30] and helps even the poor access high value products like state-of-the-art equipment [31]. It is well known that open hardware can create opportunities for distributed manufacturing that radically undercut commercial products [32-36]. For scientific hardware, for example, researchers can expect to save about 87% compared to proprietary products [37]. The savings are strongest when a form of distributed manufacturing is used (e.g. the open source self-replicating rapid prototyper (or RepRap) [38-41] dramatically reduces additive manufacturing costs [42] and increased the number of 3-D printing designs exponentially [43] that now number in the millions). The literature shows that low-cost open source 3-D printers can even reduce costs for mass manufactured consumer goods, on average by 90-99% [43,44].

These savings can be scaled to the national level by investing in the development of new open source software [45] and hardware of strategic interest to a specific country [46]. In the analysis completed in Finland, one of the secondary advantages is that imported products could be offset by manufacturing products internally from open source designs [46Heikkinen]. This advantage can be leveraged to act in the same way as a sanction if applied to undercut imports from a specific country and technology sector to increase national security and global safety. Although FOSH is becoming well-known, the strategic development of it to meet national goals outside of scientific research has not been explored.

This article reviews this opportunity by formalizing a methodology for selecting strategic national investments in open hardware development to improve national security and global safety. In the methodology, first the target criminal country that is threatening national security is identified. Next, the top imports from the target criminal country as well as potentially other importing countries (allies) are quantified. Then, hardware is identified that could undercut those imports as well as potentially other strategic exports from the target criminal country. Finally, methods to support the FOSH development are enumerated. The FOSH are designed in a way that facilitates distributed manufacturing from digital designs using local materials and tools. Thus, in addition to sanctions or instead of sanctions, supporting FOSH development can undercut the export market for the target criminal countries. To demonstrate how this theoretical method works in practice it is applied as a case study to the current military aggressor nation. It is classified as a fossil fuel exporter. Thus, how the development of energy conservation and renewable energy-based open hardware could reduce fossil fuel energy demand and the concomitant pollution, human health impacts, environmental desecration as well as financing of military operations is discussed.

2. Methods

The method used to determine strategic investments in open hardware is summarized in Figure 1.

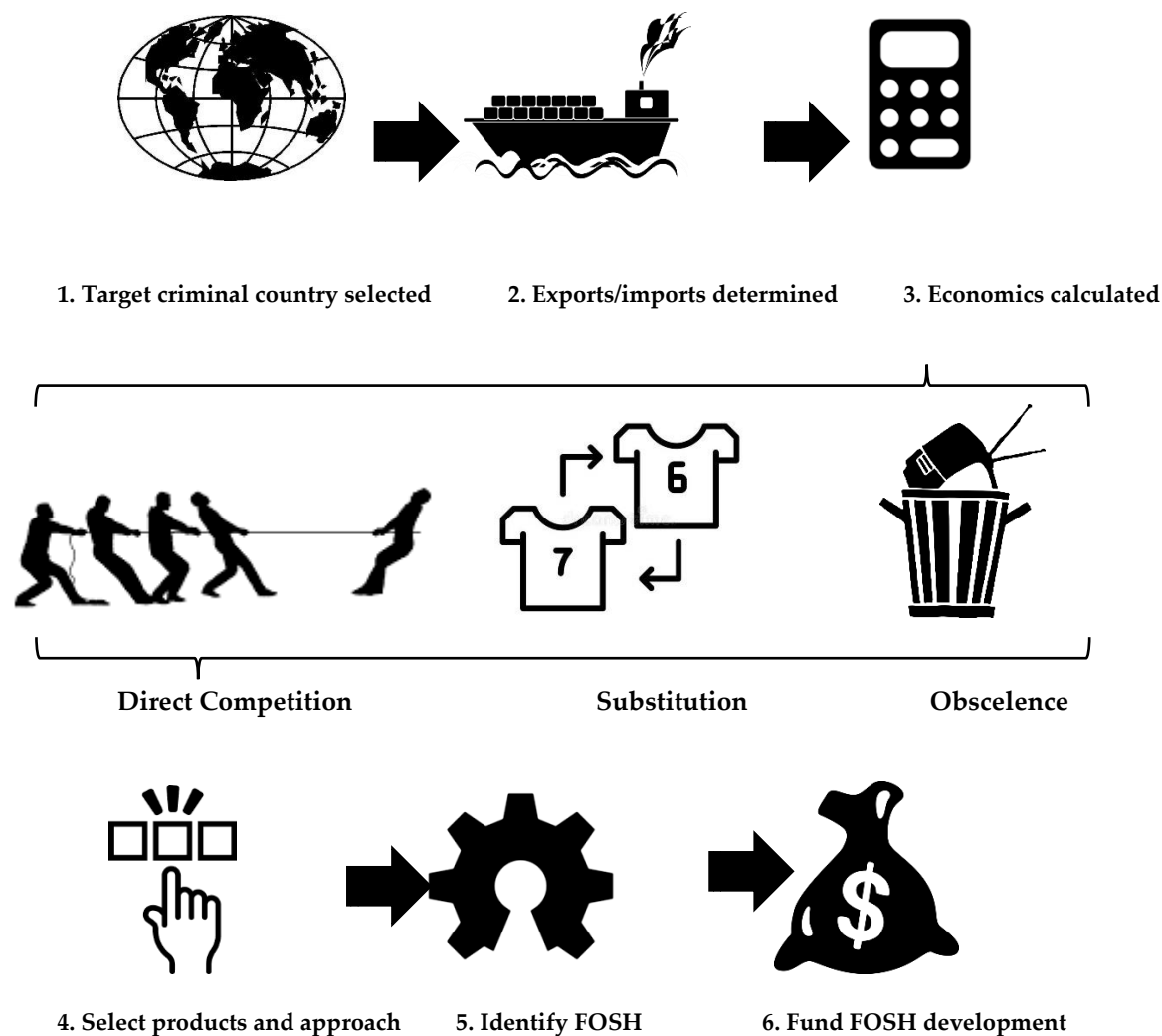


Figure 1. Flow diagram of method to determine strategic investments in open hardware.

As shown in Figure 1, first, the target criminal country is identified for disruption with strategic investment in FOSH. The target criminal country can be a political rival, an enemy or a country threatening the stability or safety of a region or the world. Next, both the major exports for the target criminal country are identified from public data as well as the imports to the country doing the analysis are identified. These imports and exports are quantified in economic terms for specific products. Then the highest value exports (and/or imports) are evaluated for the technical capacity to be disrupted by innovation. This can be determined using three approaches. First, direct competition is producing the same product at lower costs. For example, a USD \$20,000 potentiostat/galvanostat for characterizing thin-film batteries can be replaced with a USD \$100 open source model [47]. With such opportunities, products can be directly open sourced to undercut the existing market for the product. Second, substitution is replacing a product with a different one that serves the same function. For example, a study of a single open hardware toy repository found that users were offsetting USD \$60 million purchases per year by 3D printing 100 FOSH toy designs rather than purchasing similar proprietary toys [48]. For toys that were functionally equivalent the most common savings fell by 40%–90%, which represent savings expected for open source design replications of low-value products. Third, elimination of the demand for an existing product by producing a new product that makes the need for the target product obsolete. For example, Wikipedia an open source digital encyclopedia running on open source Wikimedia software made the 244-year-old paper-based Encyclopedia Britannica obsolete and it is no longer produced [49]. Wikipedia did this by creating enormous laterally-scaled value, as for example, the images on Wikimedia alone

have been valued at more than USD \$28.9 billion [50]. Wikipedia as essentially eliminated the market for hard copy encyclopedias. Finally, after the target products and innovations are selected specific open hardware is identified to reach the goal of reducing or eliminating the export of the products from the target criminal nation. Imports into one's own nation are likely the easiest to offset, but open hardware can be used to out innovate and thus reduce costs or increase functionality faster than the target criminal country's existing system (or companies within it) can innovate on its own. In addition, to the imports into one's own nation these same sources can determine other countries (allies) that are importing goods from the target criminal nation. These allies could form alliances to open hardware and leverage digital technologies [51] to use the do-it-together (DIT) methodology [52] to accomplish more than possible by going alone [53]. Since the industrial revolution a conventional centralized manufacturing model has held sway (Figure 2a) where all intellectual property is held by an organization that manufactures products and ships it to consumers. DIT consists of participatory design and collaborative production (e.g. global design and home or local manufacturing) as shown in Figure 2b. As can be seen in Figure 2, rather than have the design ideas only come from the large companies, communities and individuals can assist in developing open source designs and then the community organizations (e.g. fablabs, makerspaces as well as small and medium sized businesses) can manufacture the products locally. DIT encourages local production in a commons-based peer production strategy. Such social manufacturing generates positive externalities for all the involved stakeholders including customers, professionals and the local producers [54]. DIT is well-suited for small-scale production on local sites offering significant potential for new businesses and employment as DIT can provide competitive advantages while limiting costs and risks associated with innovation [55]. These imports, which can be converted to distributed local production, need to be quantified and hardware is identified that could undercut those imports. Thus, in addition to sanctions (or instead of sanctions), supporting FOSH development to undercut the market for the target countries by enabling distributed manufacturing of products that reduce or eliminate exported products from a targeted criminal nation.

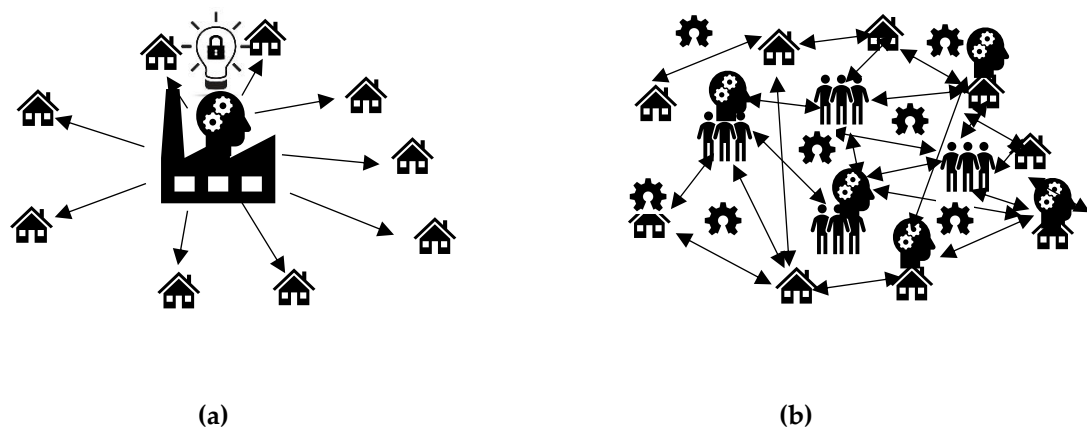


Figure 2. (a) Conventional centralized and proprietary manufacturing model and (b) the decentralized open source hardware model (design and share globally, while manufacturing locally).

3. Case Study

In order to illustrate this method, Russia was selected as an example country (step 1) for the case study. Russia a country of 142 million citizens and has a gross domestic product per capita of \$26,500 [56]. Russia also possesses thousands of nuclear weapons [57] and has continued to reproduce existing nuclear warhead designs even as it has reduced

stockpiles [58]. Thus, Russia still controls enough nuclear weapons to be past the rational limit (e.g. where using them would hurt Russians even in the best-case scenario by aggravating food shortages) and worse, plunge the world into nuclear winter single handedly, which would result in mass-starvation throughout the globe [59]. Despite its inflated military, Russia in an otherwise developing country where the average wage is only 51,100 Russian rubles per month or USD \$7,284/year [60] (e.g. the average Russia is below the poverty line in the U.S.). Russia, however, is described as an energy superpower due only to its fossil fuel reserves [61]. Russia has the largest natural gas reserves in the world (followed by Iran) [62]. Still lamenting the loss of the USSR, Russian leadership has ambitions to expand its control over regions near it [63]. This was most clearly seen by several recent acts of aggression towards its neighboring countries that came in the form of invasions. First in 2008 the Russo-Georgian War, the European Court of Human Rights ruled that Russia maintained direct control over Abkhazia and South Ossetia [64] and was responsible for grave human rights abuses [65]. In 2014, Russia invaded and annexed Crimea [66,67], which the UN General Assembly condemned the occupation of the Autonomous Republic of Crimea and part of the territory of Ukraine [68]. Finally, most recently Russia was the clear illegal aggressor with the 2022 full-scale invasion of Ukraine [69]. A full-scale war with Russia would be catastrophe even if nuclear war was prevented, so the U.S. and allies have retaliated with a long list of sanctions [70,71]. The sanctions are meant to apply economic pressure on Russia to stop aggression, the destabilization of Europe and the rest of the world, but even as these sanctions are in place, they do not permanently disable the economic engine that makes Russia's threat to global safety a reality: exporting fossil fuels. Not only do fossil fuel sales finance Russia's military [72], but fossil fuel pollution is destabilizing the global climate with severe impacts of climate change [73]. These risks include forcing 1/3 of global food production outside of a safe climate space [74], creating human health risks [75] and climate change also threatens the global economy [76].

4. Results

4.1. Case study risks from exports

To complete step 2 and 3, the top Russian exports are identified and include: 1) crude petroleum (USD \$123B), 2) refined petroleum (USD \$66.2B), 3) petroleum gas (USD \$26.3B), and 4) coal briquettes (USD \$17.6B) [77]. All of the top exports from Russia are fossil fuels, which is a serious threat to global safety if combusted resulting in greenhouse gas (GHG) emissions and concomitant climate change [78,79]. Such human-caused global climate destabilization is established with a 95% confidence [80] as are the overwhelmingly detrimental repercussions on the environment as well as human social systems [81]. The impacts of burning Russia's fossil fuel exports resulting in further climate change include:

- 1) increased global temperatures and heat waves, which already are responsible for thousands of human deaths [82-84],
- 2) increased crop failures throughout the globe [85,86], which aggravates global hunger and starvation [87-89],
- 3) increased electric grid failures and intermittent power outages [90,91],
- 4) increased droughts [92-94],
- 5) increased number and severity of forest fires [95-97],

- 6) increased sea level rise, which submerges low-lying coastal areas and increases shoreline erosion [98,99],
- 7) increased saltwater intrusion [99,100], which can threaten drinking water supplies [101],
- 8) increased storm damage to coast lines and increased flood risks [102-106].

4.2. Case study FOSH targets

4.2.1. FOSH for electric vehicles

For step 4, the profit centers of Russia's fossil fuel industry will be targeted systematically with open hardware (step 5). As the first two profit centers for Russia focus on both crude and refined petroleum targeted investments in open source development revolve around those that antique the internal combustion engine that burns gasoline or diesel fuel. Any hardware that reduces the need for gas-based automobiles could be of some help (e.g. improved public transportation, equipment for telecommuting). Currently, however, electric vehicles (EV) offer the best potential for elimination of fossil-fuel-based land transport and are already gaining market share [107], having more than doubled in 2021 [108]. Despite this growth, there are still several technical challenges to overcome [109] to reduce EV costs (and their batteries [110]) to accelerate the obsolescence of the use of oil for internal combustion engines altogether.

There is already some FOSH development revolving around EVs. Support for open source development to support EV charging stations [111] exists. In addition, Tesla unlocked its EV patents [112]. Shortly after Ford, also announced opening its portfolio of previously patented EV technologies in an effort to accelerate industry-wide development [113]. Open source battery management has been developed [114]. FOSH has also been developed for in-situ monitoring of Li-ion cells [115], maintenance tool for light-electric-vehicle batteries [116] and research has been done on a line of open source all iron batteries [117, 118].

Further open source development of batteries and electronics could all be expected to reduce the capital and operating costs of EVs helping to further the diffusion of the technology and for eliminating oil for transportation. In addition, there is an opportunity for distributed manufacturing of EV components and potentially entire vehicles in high population density regions.

4.2.2. FOSH for energy conservation

The third profit center is petroleum gas or natural gas, which is primarily used to heat buildings in Europe although it is also burned to generate electric power. There are several areas that could benefit from open source development that would reduce natural gas use for heating and some are already underway. Open hardware that is part of the internet of things (IOT) [119,120] is used for low energy consumption devices [121], monitoring power quality and energy savings [122]. There are numerous FOSH methods that have been developed for power monitoring [123-126], and smart meters [127-129] including those for institutional buildings (i.e. schools) [130]. FOSH is also used to improve energy efficiency and demand response [131] as well as smart converters [132] and microgrid communications [133]. There are also opportunities to develop open source smart sockets, programmable thermostats, and LED lighting.

Related to conservation, development of open source technologies could also take the form of those that help improve energy efficiency for physical testing such as an open

source blower door [134] to help identify air leaks in buildings. This technology could enable library-check out style of the device to help retrofit homes in an area. Other devices in this class would be thermal imaging cameras to detect improper insulation or faulty windows. Similarly, reducing heat loss can also be reduced with insulation. So open source development could reduce the cost of insulation by providing the tools to turn local materials into insulating materials. The clearest opportunity would be the machinery at the fablab scale [135,136] to convert newspaper and fire retardant into cellulose insulation [137]. Although, it should be pointed out, that the costs of all of the types of insulation may benefit from open source distributed manufacturing such as FOSH methods to make fibers [138].

4.2.3. FOSH for heat pumps

With the invasion of the Ukraine the EU has already unveiled a strategy to eliminate their dependence on Russian natural gas [139]. Energy conservation, however, is not going to be enough to do it and the other approach is to electrify heating to not only cut down on natural gas, but to eliminate its use (and thus the demand from Russia) all together. One promising upcoming technology to do this is heat pumps – both ground source and air source. Heat pump systems are often uneconomic unless coupled with solar power for offsetting natural gas or propane fuels [140,141]. Open source development for a heat pump is already underway [142]. Future work could focus on FOSH for local fabrication of heat exchangers, pumps, motors, and piping. Ground source heat pumps would benefit from open hardware development of bore hole drilling units, such as an Open Source Ecology tractor [143] attachment.

4.2.4 FOSH for renewable energy

The fourth profit center for Russia is exporting coal, which is most commonly combusted for electricity. It should be pointed out here that even if EV scaling eliminates internal combustion engine-based vehicles and heat pumps offset the need for burning natural gas for heat, to completely eliminate the need for fossil fuels from Russia, electricity from other sources must be generated. According to the International Energy Agency, wind and solar, are the fastest growing sources of energy [144]. Choi et al. developed a renewable energy monitoring system [145], which is a start towards FOSH development in the renewable energy space. Although, there are now FOSH-based hardware in the loop simulators for wind turbine testing [146] and there is some potential for open source small wind turbines [147], there is less of an opportunity for small-scale distributed production with wind than solar.

Solar photovoltaic (PV) is particularly promising because it is more geographically diverse – available to most of humanity and growing rapidly [148,149]. PV is sustainable [150], a net energy producer [151] with an excellent ecological balance sheet [152,153]. The capital costs for PV are dropping rapidly (60% in the last decade) [154-157]. Because of this, already large-scale PV is generally the least cost option for generating electricity [158]. Despite the lifetime economic benefits of PV, capital costs are the primary barrier to faster deployment, in the developing [159] and developed nations [160]. There are several approaches to reducing upfront PV costs including small-scale do-it-yourself (DIY) [161], which can cut more than half of the cost by eliminating most labor and soft costs.

The majority of PV system cost declines were caused by the \$/W declines in the cost of PV modules, but racking, electronics, and wiring have seen far lower rates of cost decline [162]. PV costs can be more manageable if broken in small components that can be purchased over time, rather than all at once. For example, plug-and-play solar, where PV modules are connected with microinverters directly to the household circuits by

consumers is technically possible [163-167], but regulations have stalled scaling of the technology in much of the world even though it allows the poor to enter the PV market [168]. There are currently no FOSH based microinverters, which is a large opportunity to reduce solar costs. Such microinverters would need to be developed for all of the globe's standard voltages.

Secondly, racking is focused proprietary and costly designs, and racking costs dominate the cost of small PV systems [161]. There are, however, FOSH designs that substantially reduce racking costs for low-tilt angle ground mounts, which result in 85% and 92% savings from proprietary alternatives [169], large scale ground mounts with low-concentration reflectors [170], tensegrity structures (saved up to 77%) [171], and small-scale agri-voltaic cold frames [172]. For buildings there are also FOSH designs for flat roofs that save over 80% [173], RV rooftops mounts [174], and post-market module retrofits for building integrated PV [175]. In addition, to fixed mounts FOSH solar trackers [176-178] and dual axis trackers [179] have been developed. Far more work is needed to develop the lowest cost FOSH designs for PV racks based on the availability of materials locally for all parts of the world so that all communities can take advantage of these generally >75% savings.

Research into improving the PV industry can also benefit from open source design [180]. Currently, no PV manufacturer is able to use all the known improvements to device performance and opportunities exist for opening up patents in the PV space similar to what Tesla and Ford has done for EVs. Open source is mature, however, in part of the PV technical ecosystem: software. There is already extensive open source software to assist in PV system design including PVLlib [181,182] and the National Renewable Energy Lab's Systems Advisory Model [183,184] as well as a module emulator [185] and FOSS for modeling advanced inverters [186]. FOSS has also been developed to determine the PV potential in urban areas [187] or over entire regions with open source geographic information system software [188].

In addition, the Open Source Outdoors Testing Facility provides open access data on PV systems in northern environments [189] and could be replicated in other parts of the world. Any outdoor testing facility can reduce capital cost for monitoring using open source systems for real time measurement of the sunlight incident angle [190], for UV-Vis-NIR radiation measurements [191] and radiation shields for environmental sensors [192]. Modules can be tested on site or in the lab with a solar simulator using an open source IV curve tracer for solar [193]. There is also considerable FOSH developed for monitoring PV systems including data logging [194] and those for monitoring PV device performance [195], insitu monitoring of smart PV modules [196], system monitoring [197], monitoring PV plants [198], and remote monitoring [199,200]. FOSH has also been developed to monitor PV integrated into microgrid [201, 202] and smart monitoring [203]. All of this solar-related FOSH can be further improved to be completely digitally manufactured so that communities could locally manufacture as much of the system as possible from local materials.

5. Discussion

5.1. Countries positioned to use the FOSH model

Russia exports primarily to the EU (USD \$188), China (USD \$58.1B), Netherlands (USD \$41.7B), Belarus (USD \$20.5B), Germany (USD \$18.9B), and Italy (USD \$16.7B) [204]. Thus, these countries are in the best position to spear-head the FOSH development recommended from the results of this study. Europe is particularly well endowed with fab-labs and makerspaces as shown in Figure 3 [205]. Thus, they are well-prepared to follow a distributed manufacturing (e.g. DIT) model to fabricate EVs, energy conservation

equipment and renewable energy like PV FOSH. In addition, China is already a major open source technology proponent [206]. China, for example, developed the open source Kylin operating system, and by 2019, a NeoKylin variant was compatible with more than 4,000 software and hardware products and ships pre-installed on most computers sold in China [207]. Combined, Kylin and Neokylin dominate the domestic Chinese market with over 90% of the operating system market share in the government sector [208]. In addition, China is already the leading manufacturer of solar photovoltaics modules, and thus appears well positioned to benefit from FOSH development of peripheral technologies (e.g. racking and electronics) that would increase the size of their market throughout the world faster than it is already increasing.

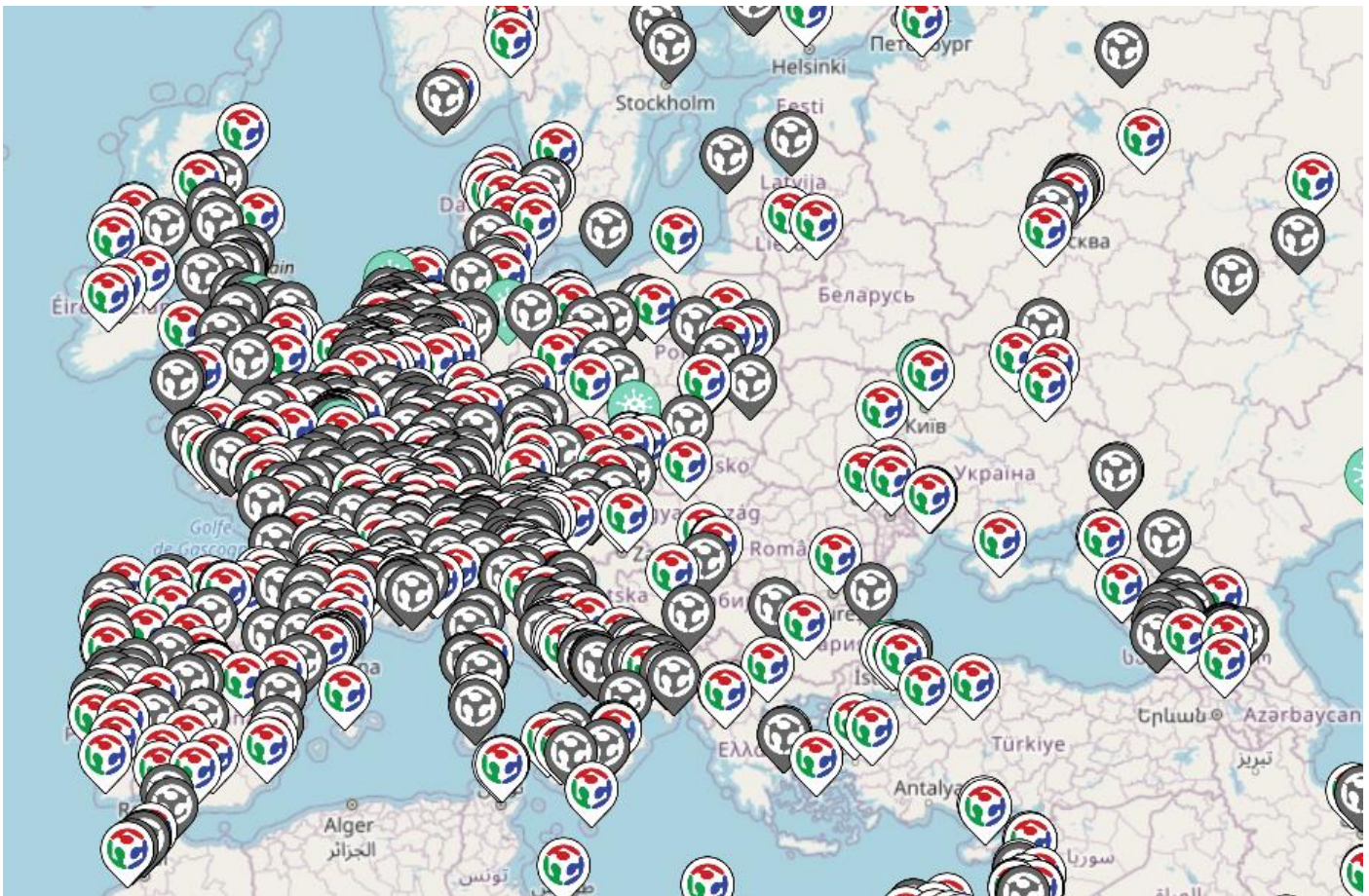


Figure 3. Fablabs in Europe [205].

5.2. Target Response

If a wave of FOSH was developed that made energy conservation, heat pumps, EVs and PV extremely inexpensive to manufacture locally, and country's that import Russia's goods adopted the 'design global - manufacture local' system, Russia's current fossil-fuel export model would be made obsolete. If Russia attempted to maintain business as usual it would be economically devastating. As this would be a distributed method of resistance and any retaliation would be against customers, such retaliation would be futile. Instead, of maintaining the status quo as an aggressor nation and fossil-fuel exporter, Russia has the opportunity to lift its own citizens out of poverty [209] by leveraging the FOSH funded by external countries to manufacture fossil-fuel conserving products to meet their own domestic demand and help transition them to a sustainable more diversified economy. This would not only help improve climate stability, but it would also directly improve domestic economic security and thus the perceived need for militarization and aggression.

5.3 Funding national strategic FOSH development

There are several ways the open hardware development identified in section 4 could be funded. First, federal governments can use standard calls for proposals (CFPs) specifically requiring open source licensing of the FOSH technologies listed. Already, for example, the U.S. National Science Foundation (NSF) is investing USD \$20 million in the Pathways to Enable Open-Source Ecosystems (POSE) program [210]. The NSF aims to “harness the power of open-source development for the creation of new technology solutions to problems of national and societal importance” [210]. Prior work has shown that open source investment should result in an extremely high return on investment in FOSH [29]. The funding would work as normal university or industry grants/contracts, with the exception that rather than fund people and allow them to gain a monopoly on the intellectual property, instead there would be an open source license agreement mandate. Surveys indicate that the vast majority of faculty would be amenable to open source development as they would accept an open source endowed chair requiring them to open source all of their work [211]. Additionally, national and international funding agencies may wish to sponsor challenges or contests like the XPRIZE to can promote development of FOSH toward specific technical goals by offering “bounties”, scholarships, tax breaks, national park passes, awards or even citizenship.

In addition, to funding and incentivizing FOSH development, governments can also use their purchasing power to accelerate the adoption of FOSH developed in the national interest. This can be done by having purchasing policy preferences for open source technologies. This would include prioritizing funding for open source technologies over purchasing proprietary commercial products. The government could also make bulk purchases of materials or provide tax breaks for those manufacturing or purchasing FOSH that supports the national interests. Lastly, national governments have the opportunity of creating a free online database of tested, vetted, and validated FOSH to further national interests. It could act equivalent to a digital twin model being used in industry [212]. The database would include the bill of materials (BOMs), digital designs files (e.g. CAD), instructions for assembly and operation, and raw source code for all software and firmware. In order to vet designs governments could provide funding to universities, companies, and/or utilize technical staff at government labs. Already the U.S. National Institute of Health maintains an open design database called the 3-D Print Exchange [213] and the United Nations is evaluating starting an open hardware database for appropriate technology to meet its sustainable development goals [214].

6. Conclusions

This article has reviewed the opportunity to take advantage of the innovation acceleration and economic savings provided by open source design coupled to distributed manufacturing by formalizing a methodology for selecting strategic national investments in open hardware development to improve national security and global safety. The method was explained in detail along with a summary of ways to support the FOSH development. For this method to work and scale, FOSH are designed in a way that facilitates distributed manufacturing from digital designs and then made using local materials and tools. Thus, in addition to sanctions or instead of sanctions, nations now have the option of supporting FOSH development to undercut the export market for target criminal countries.

Some of the largest current threats to humanity come from both acts of military aggression and climate destabilization. As the case study results in this review show, by investing in FOSH development of technologies for energy conservation, EVs, heat pumps and renewable energy technologies, nations of good will have the opportunity to radically reduce costs and thus accelerate the diffusion of these technologies that can move

humanity towards a sustainable state. With freely available open source designs of these technologies able to be manufactured locally, as for example in makerspaces and fablabs, the adoption of these technologies can play a strategic role in economically limiting criminal fossil-fuel states, while also helping to limit the negative impacts of global warming.

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