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User Innovation in Military Drone Development

The Russo-Ukrainian War 2022-2025

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User Innovation in Military Drone Development: The Russo-Ukrainian War 2022-2025

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Abstract

Following the Russian invasion of Ukraine in 2022, drones have come to pervade the battlefield and changed modern war. This study examines the innovation processes underpinning this technological development. Departing from theories of user innovation, it asks *what is the role of users in military drone innovation in the Ukrainian Armed Forces, and how does user innovation operate at the scale observed in the conflict?* Based on an abductive analysis of media reports from major Western news outlets, as well as an assemblage of reports and whitepapers from Ukrainian sources and a diversity of Western analysts, we make several observations. We find broad support for the notion that frontline users have been central to Ukrainian drone innovation, especially when taking into account behavioral innovation and experimentation with product configurations. To occur, however, this user innovation appears to be dependent on pre-existing knowledge stocks and the exposure of technologically sophisticated individuals to high-need user roles, as well as on organizing principles that are unconventional in military units. To scale, user innovation also appears dependent on producer firms with high levels of absorptive capacity and specialization in several distinct manufacturing niches that complement and enable frontline user innovation.

Policy implications

One central policy implication from previous studies on Ukrainian drone-technology related innovations is that continues dialogue with drone users on the frontline is essential to modify and develop drones (Braunerhjelm and Brychko 2025a). The present study emphasizes the importance of a 'tight-loop' user-producer interactions. It gives nuanced insights into an innovation system that is uniquely capable of user innovation and of absorption of those innovations *and* user-related knowledge into producer firms.

Based on this, the report suggest that procurement and industrial policy focus not just on narrow concern about building up equipment stocks in the short term and, in the slightly longer term, industrial capacity to produce and innovate in producer-centric ways. Rather, the analysis suggests that we might preferentially support building up innovation systems that are organized to engage maximally with the kind of rapid, adaptive innovation that happens close to the front-line.

Although this report does not empirically address the Swedish system, lessons can still be drawn from the Ukrainian analysis that are relevant to innovation policy in general, as well as to Swedish policymaking. Several possible pathways for the government to support such a tight-loop user-producer interaction are explored in this report, concerning both military R&D and civilian R&D.

Implications for military R&D

- Procure Modular Military Systems
    - Militaries could procure systems that are not fully integrated, contrary to traditional procurement practices. This allows systems to serve as modifiable platforms tailored to specific needs. It enables both production at scale and rapid modifications for urgent requirements.
- Military Governance that Enables Tight-Loop User-Producer Interaction
    - Enhance Technical Training
      Soldiers should receive more advanced technical training from the military. Peacetime efforts could also build drone expertise within the civilian technical workforce. This will cultivate more innovative users.
    - Foster Cultural Change
      Promote a cultural shift toward innovation in the military by explicitly allowing more soldiers opportunities for 'permissionless' innovation. This will boost the level of experimentation.
    - Enhance Technical Support
      Provide technical support directly to soldiers. Introduce drone mechanics and workshops at lower echelons for soldiers. This reduces experimentation barriers caused by limited technical skills.
- Involve Innovative Users
  Producers should involve innovative users.
  This has important implications for managing innovative firms in the military sector. Build capacity to absorb use-related knowledge by hiring user innovators or fostering close relationships with frontline users.

Implications of publicly financed civilian R&D

A large body of literature has convincingly documented that user innovation occurs widely across the economy. While the earliest documentary evidence came from niche fields (e.g. von Hippel, 1976), subsequent scholarship documented that up to a third of users in fields like open-source software, surgical equipment, and extreme sports developed innovations for their own use (von Hippel, 2005). Representative surveys of firms found that up to forty percent of them developed process innovations for in-house use (i.e. as users), while representative surveys of consumers found that up to six percent of all consumers develop innovations for their own use (de Jong, 2016).

A case study, such as this study, is an in-depth analysis of a particular setting in time and place. However, the actual phenomena of user and producer interaction are similar, and we would therefore suggest a set of policy-related insights from the literature for the civilian sector which is in alignment with what found in this case study.

- Supply of human capital with technological skills. Engineers are overrepresented among user innovators (Bengtsson & Edquist, 2022), and Bloom et al. (2019) provide evidence that a higher share of STEM-educated individuals contributes to greater innovation in the economy. The Ukrainian case supports this pattern, showing that technical skill training has dual-use effects—stimulating innovation in both civilian and military sectors. Policies that promote early technical training, for example integrating technology education in schools, can therefore expand the supply of technically skilled users.
- Access to technological infrastructure. Evidence from Ukraine and other contexts suggests that user access to technological tools in the civilian sector can enhance innovation (Svensson & Hartmann, 2018). Policymakers can strengthen this effect by supporting technology infrastructure—such as subsidizing broadband expansion (Åkerman, 2015) or establishing maker spaces in public institutions like hospitals (Svensson & Hartmann, 2018).

See Bengtsson and Edquist (2022) for additional policy tools that differ from the traditional ones focused primarily on incumbent firms and academic institutions.

Important caveats – costs and trade-offs of doing what the Ukrainian forces are doing

High costs and trade-offs. Even if the innovation dynamics observed in this study could be replicated, it is not obvious that other countries will be willing to bear the costs and trade-offs of doing so. Especially not in countries that does not face an existential threat to their sovereignty. Our analysis makes clear that the costs (both monetary and non-monetary) of doing what the Ukrainian forces are doing are very substantial.

Risk for standardization failures. The reliance on widespread innovation across the military frontline create challenges of coordinating across, and ensuring compatibility between, technological systems that may not be desirable for all countries. This may especially be the case for countries whose defense depends on alliances with high levels of international coordination and standardization.

Risk for corruption. Moreover, the proximity of producers to military units, as well as the discretion afforded to Ukrainian military commanders, might also create a range of problems around governance and corruption risks that are non-trivial to handle.

Executive summary

The Russo-Ukrainian War, 2022-present, has seen immense expansion in the scale and scope of drone use on the battlefield. This expansion has been enabled by extensive innovation drone technology, in drone-related technology, and in how drones are used and deployed. In this report, we examine the innovation processes that underpin these developments and kind of organizations that enable both the rapid development and large-scale deployment of drones on the battlefield. We posit that the innovation process that we observe on the Ukrainian side of the conflict can be understood as resulting from 'tight-loop' user-producer interactions within an innovation system that is uniquely capable of user innovation and of absorption of those innovations and use-related knowledge into producer firms.

Today, many countries seek to understand and learn from Ukraine's ability to continuously develop, adapt, and deploy drone-related technologies in the context of drone-centric warfare. The Ukrainian experience demonstrates how tight coupling between users and producers can generate rapid and sustained adaptive capacity in high-intensity and uncertain environments. For a small, technologically advanced country such as Sweden—whose defense relies on qualitative technological advantage rather than numerical superiority—understanding how such adaptive innovation capacity can be built and sustained is therefore of clear military-strategic importance.

Beyond these strategic considerations, the Ukrainian case is also highly relevant for industrial and innovation policymakers concerned with the organization of military and civilian R&D. It challenges the prevailing model in which innovation tasks are primarily delegated to producers through formal R&D programs and procurement processes, instead illustrating a division of innovative labor where users drive problem identification, experimentation, and early solutions, while producers focus on scaling, industrialization, and system integration. As an analytically rich example of an innovation system in which user and producer innovation are systematically integrated, the Ukrainian experience offers important insights for Swedish industrial and innovation policy—particularly in areas where civilian and military technologies intersect—into how R&D systems can be designed to better leverage technically skilled users, rapid feedback loops, and complementary producer strategies.

Our findings are based on an abductive study of a wide range of publicly available material (news media reporting, government and industry reports and whitepapers, specialist media analyses) focused on the Ukrainian side of the conflict. This analytical approach, common in studies of industry development and the evolution of new markets and product categories, allows us to observe detailed cases from across the Ukrainian theater in a way that is not possible without either well-structured, wide coverage databases or very extensive fieldwork. However, this approach entails trade-offs and it necessarily implies that we rely on selective reporting from an information-controlled environment, which introduces limitations into the data. We take numerous methodological steps to address these limitations but cannot resolve them all.

Frontline user innovators are a significant source of innovation

Based on this analysis, we observe that frontline user innovators (i.e. soldiers and military organizations innovating in order to use their innovations for themselves) have been a significant source of innovation. Users have engaged in extensive modification and augmentation of drones, identified new applications and uses of drones, developed functionally novel types of drones, and developed new tactics and methods for using drones on the battlefield.

Enablers influencing the user-oriented innovation process

We also document that this user-oriented innovation process has been enabled by five developments: a change in military culture, deployment of technically literate individuals into user roles, concentration of innovative users in leading-edge units, sharing of drone-related needs and innovations with absorption-capable producers, and user-complementing producer specializations.

User innovation within the Ukrainian Armed Forces has been enabled by considerable tolerance for, and encouragement of, experimentation with both material and tactics and an acceptance of non-standardized practices across and within units. Moreover, successful innovations are shared widely. This change in military 'culture' has lowered the barriers to user innovation and innovation diffusion and allowed the Ukrainian forces to leverage the innovative capacity of frontline soldiers much more extensively than what can usually be observed in military organizations, especially during peacetime.

One striking feature of user innovators within the Ukrainian forces is that these users frequently possess, or have access to, high levels of skill in drone-relevant technology domains (e.g. software development, engineering, drone design). Due to the drafting practices of the Ukrainian forces and the structure of Ukrainian industry and educational systems, frontline soldiers find themselves able to work with, develop, and modify drone technologies because they possess the relevant technical knowledge to develop working solution. Moreover, Ukrainian forces have organized to deploy technically skilled workers close to the frontlines in 'drone workshops' that allow frontline soldiers access to the technical support necessary to realize innovative ideas. This creates a situation where users have access to, and can combine, understandings of frontline needs ('problem knowledge') with understanding of technical possibilities for addressing them ('solution knowledge').

Innovative users are not widely scattered across the Ukrainian forces. On the contrary, they are concentrated in ('leading-edge') units with particularly advanced practices around drone use. The Ukrainian forces have systems that allow units that are particularly adept in using drones to be identified (through e.g. scoreboards), and both innovative users and new technology are preferentially channeled into those units. This allows for the formation of innovative user communities within the Ukrainian forces, where innovators can support each other, share innovations, and develop on each other's innovations.

Another striking feature of user innovation within the Ukrainian forces is that user innovations and user needs are shared not just *within* individual units or the Ukrainian Armed Forces at large, but also with producer firms: producer firms participate in drone-related communication forums with frontline users, are embedded in drone-using units, undertake training of drone users, and employ (or are founded by) formed users. This allows for the rapid dissemination of otherwise costly-to-transfer needs, ideas, and innovations with firms that can then contribute to, or scale up, innovations. It also provides producer firms more ready access to lead users that might otherwise be difficult to identify and creates opportunities for rapid testing and refinement of producer-developed solutions.

Producers also specialize in distinct niches that enable various forms of user innovation to occur and be leveraged at scale. Four such niches are worth emphasizing. Some producers concentrate on producing standardized components at scale in order to reduce unit costs, but then do so in ways that allow users to creatively recombine those components to develop integrated systems to serve particular battlefield roles. Other producers concentrate on developing products as platforms that are explicitly designed for users to innovate on, such that a standard producer-developed drone can be customized for a range roles. Yet other producers concentrate on producing modular additions that can integrate with other systems. Such additions will often have been prototyped by users but can be more efficiently produced at scale by producers. Finally, there are producers that concentrate on productizing user-developed behavioral innovations.

‘Tight-loop’ user-producer interactions

Taken together, we posit that the innovation process that we observe on the Ukrainian side of the conflict can be understood as resulting from ‘tight-loop’ user-producer interactions within an innovation system that is uniquely capable of user innovation *and* of absorption of those innovations and use-related knowledge into producer firms.

1. Introduction

The use of military drones in the Russo-Ukrainian War has been widely reported following Russia's full-scale invasion of Ukraine in 2022. Reports have clearly evidenced the increasing importance of drones on the battlefield, a development that has attracted considerable attention from military analysts and security scholars and raised important questions about future conflicts. In this paper, we are concerned with a different set of questions associated with the rise to prominence of drones during the conflict, namely those around the *how* innovation in drone technology unfolds, the *complementarities* between different forms of innovation, and the *organization* of the systems that bring drones to the battlefield. As such, our work should not be read as advancing a debate on the military implications of drones, but rather as contributing to a discussion of the functioning of the drone industry and possible pathways for supporting such an industry. It should, in other words, be read alongside work such as that of Braunerhjelm & Brychko (2025a, 2025b) or Matlack et al (2025), as illuminating what we can learn from Ukraine's ability to continuously produce and innovate drone-related technology. For a small, technologically advanced country such as Sweden, whose defense relies more on qualitative technological advantage than on numerical superiority, understanding how such adaptive innovation capacity can be built and sustained is of clear strategic importance.

Our analysis of these questions departs from theories of *user innovation* (von Hippel, 2005). User innovation literature posits that *users* of technologies frequently play a key role in technology development, and recent work has documented the role of user innovation also in military contexts (e.g. Lindsay, 2010; Foley, 2012; Kollars, 2015, 2017; Hartmann & Hartmann, 2023). Especially *lead users* (von Hippel, 1986) have been shown to frequently develop solutions that are substantially ahead of market trends, and users generally have been shown to develop novel solutions, or modify existing ones, to address idiosyncratic needs (de Jong, 2016), especially as regards 'behavioral innovations' (Von Hippel et al, 2024). It is clear that users are efficient innovators, and that they frequently are able to self-produce the innovations they design at low cost (Hienerth et al, 2014). It is, however, also clear that supporting users (e.g. by providing access to design tools, production equipment, etc.) allows *many* more users to develop innovations, and to develop more valuable ones (Franke & Piller, 2004; Svensson & Hartmann, 2018). Given appropriate means of diffusing innovations, there is evidence that groups of users can compete with, or crucially complement, producer firms (Gambardella et al, 2016; von Hippel, 2017).

Based on an abductive analysis of reporting about the Russo-Ukrainian War in Western media as well whitepapers and reports published by Ukrainian government, industry, NGOs, and think tanks, we make several observations of the nature of drone development. Firstly, we demonstrate that the widely reported innovation in drone technology is best understood as innovation within a technology system. While material and tactical innovations are widely recognized and celebrated, these innovations crucially depend on innovations in software, connective infrastructure, and counter-counter-measures, as well as in techniques and training that allow drones to become useful on the battlefield. Second, we provide much-needed nuance to the celebrated 'MacGyverism' and 'open source practices' of the Ukrainian Armed Forces. While it is true that the Ukrainian armed forces have been able to leverage user innovation through emergent, bottom-up innovation

processes, this process depends on pre-existing knowledge stocks, novel organizational practices, and porous organizational boundaries. Finally, we argue that while a user-dominated innovation process characterized the early stages of the conflict following Russia's invasion, this model was quickly complemented by what we term a *tight-loop user-producer interaction* without which the scale of drone deployment on the battlefield is straightforwardly unimaginable.

Understanding these developments clearly have implications for both defense policy and industrial policy. The ability to rapidly develop, produce and implement drones and military innovation more broadly matters to national defense, and understanding the conditions that have enabled Ukraine's to effectively innovate while also mass-producing drones may be instructive for other countries interested in building up their national military capabilities in this domain and others. Furthermore, military innovation has historically been 'upstream' of private-sector innovation, with technologies and human capital developed for defense purposes funded by defense spending 'spilling over' into private industry. In a scenario where geopolitical shifts are likely to entail substantial investments both in military R&D and in the building up military capabilities, understanding the systems that enable rapid and proficient military innovation is likely to be of substantial value. These systems, as we observe them, have implications for both the military and the civilian public R&D system, for military technology procurement, and for how civilian and military technology development interact.

Besides military strategic reasons, there are, however, several other reasons to learn from the Ukrainian experience of innovating, developing and deploying drones. The case is also highly relevant to industry policy makers concerned with supporting R&D and procurement outside of the military context. The Ukrainian case challenges the prevailing model in which innovation tasks are primarily assigned to producers through formal R&D programs and procurement processes. Instead, it illustrates a division of innovative labor in which users drive problem identification, experimentation, and early solutions, while producers focus on scaling, industrialization, and system integration. This has direct relevance for the Swedish defense and security industry, where procurement structures and R&D governance strongly shape which innovation pathways are pursued, but also illustrates how organizations in other fields might also benefit from external sources of innovation.

Moreover, research on civilian innovation has shown that user innovation can play a decisive role, but that its importance varies across sectors and institutional contexts. The Ukrainian innovation system represents an extreme but analytically valuable case in which user innovation is systematically integrated with producer innovation. For Swedish industrial and innovation policy—particularly in areas where civilian and military technologies intersect—this offers important insights into how R&D systems can be organized to better leverage technically skilled users, rapid feedback loops, and complementary producer strategies.

2. Military Drone Innovation and The Russo-Ukrainian War

The phase of the Russo-Ukrainian War that we focus on in the study began with Russia's full-scale invasion of neighboring Ukraine in March of 2022. This phase of the war was preceded by Russia's annexation of the Crimean Peninsula in 2014 through the use of paramilitary forces. This annexation was followed by fighting between Ukrainian forces Russian-supported separatist groups in the Donbas region of Eastern Ukraine, repeat incidents involving navy and air force vessels, and escalating cyberwarfare. In late 2021, Russia amassed sizable military forces on the Ukrainian border and, in early 2022, initiated what Russia until recently has described as a "special military operation". Despite repeated calls for negotiations and ceasefires, the conflict continues three years after Russia's invasion.

While many things are striking about the Russo-Ukrainian War, one particularly striking feature is that it began in many respects a 20th century war: it is full-scale 'conventional conflict', a slow and grinding war fought over conflict of territory and infrastructure, with infantry divisions and mass conscription, with tanks and trenches and artillery and bomber planes, with landmines and bullets, with bombing and destruction of Ukrainian cities, with enormous casualties on both sides. In key respects, this is a war that in its means and execution remains akin to World War II. This is a far cry from the high-precision, high-velocity, special force-centric visions of unconventional war that military planners and strategists might have envisioned in the 2000s and 2010s as they sought to draw lessons from the expeditionary forces and asymmetric conflicts of those decades.

One startling difference between this war and prior ones, however, is the rise to prominence of drones. While drones are not at all new in modern warfare (e.g. Chamayou, 2015), the Russo-Ukrainian War of the 2020s is the first large-scale, high intensity war where both sides have extensively deployed military and commercial drones (Kunertova 2023a). The military use of unarmed UAVs spans more than 50 years, with Israel pioneering the use of live-streaming high-resolution footage in 1992 (Bergman 2018, 352; Borg 2021, 402). Moreover, drones were prominently used as part of the War on Terror, serving in a highly specialized recognizance role and conducting approx. 400 air strikes on terrorist targets in Yemen, Pakistan, Somalia, and the Philippines, they incurred only very limited technological and tactical change during this period. As a result, before the war in Ukraine, military use of drones was most often studied within a particular strategic context characterized by irregular warfare operations in permissive environments (Mayer 2015, 765). As for smaller commercial drones, the Islamic State modified and used COTS drones from 2016 to drop munitions on targets, as well as to direct mortar and rocket fire in a systems-based targeting approach (Rassler, 2018; Spansvoll, 2024), foreshadowing the techniques and adaptations currently observed in Ukraine.

However, as King argues: "In the last two decades, there have been some remarkable developments. Drones have moved from playing a small surveillance role to becoming an indispensable battlefield weapon" ((King 2024, 2). This new and expanded role as a weapons system sits at the core of the current focus on drones as an emergent military

technology. As one of the most notable developments of the war in Ukraine (Pettyjohn 2024), this near-term trajectory has been radically accelerated. Characteristic of the (near) peer-to-peer war, drones are within this conflict used in highly contested environments as platforms for reconnaissance, for strikes using attached munitions, in addition to guiding artillery targeting and battle damage assessment (Nagl and Crombe 2024, 13). Reportedly, no unit would attempt to '[…] manoeuvre or launch an assault without at least one small commercial drone to scout' (Pettyjohn 2024), with drones having enabled a shift towards dynamic targeting reliant on time-sensitive data (Bradley 2024, 107). In such an environment, the two opposing sides are innovating to maintain what appear to be very marginal and very transitory operational advantages.

Scholars and military analysts have, thus far, done excellent work to understand the strategic and tactical implications for drones on future conflicts, and security scholars have similarly done excellent work to highlight the implications for national and international security of this new technology. Substantial academic attention has been paid to drone technology, its effectiveness, implications for warfare, and the political calculations surrounding its use (e.g. Cronin 2013; Sloggett 2014; Mayer 2015; Aleksander 2018; Walsh and Schulzke 2018; Lunsford and Bradley 2022; Mohsan et al. 2023; Kreps and Lushenko 2023), as well as the ethics of 'responsible' use, which remains a contested topic (Boyle 2015; Gregory 2017; Enemark 2020). Scholars have contemplated whether drones clear the threshold for a military revolution, under which conditions they offer an operational advantage, and how they may alter the costs and benefits of using armed force for both the actors wielding them and their targets (Horowitz et al. 2016, 7; Kreps & Lushenko 2023; Rossiter 2023; Walsh & Schulzke 2018).

Contrary to the expectations of military analysts, drone proliferation within this war has *not* been constrained by high financial, technical, and infrastructural requisites. Both sides have followed a different model of adoption by leveraging low-cost commercial platforms (Chávez and Swed 2023). Both militaries are relying heavily on drones in different forms to conduct intelligence, surveillance and reconnaissance, artillery spotting, combat and one-way missions. Notably, the use of strictly military-grade UAV technology has been complemented by the unprecedented application of cheaper, numerous and more attritable commercial (COTS) drones (Bendett & Nersiyan, 2024). Kunertova illustrates how the myriad of small drones has changed battlefield dynamics, acting as scouts, loitering grenades, drone bomblets, and suicide drones, without the presumed need for air superiority expected by strategic studies scholars (2023b). At the same time, there has been a considerable expansion also in other types of drones (a topic that we return to in our analysis).

Our interest in this study is not with questions of security, strategy, or tactics. We leave that to other studies and other scholars. What we are interested in is the *innovation systems*, i.e. the actors and innovational dynamics that allow for both the rapid development of drones as a technology and for the mass-production of them. We want to understand how drones, understood as technological systems, are developed and the process through which that development occurs and interacts with large-scale production systems. Our study, in other words, is not primarily intended for military planners or strategy, but for the defence industry innovation managers, industrial policy policymakers, and military

procurement specialists thinking about how to build supply chains and support industrial development in a way that will allow military organizations to access the quality and quantity of drones they might need. It stands to reason: the challenge for the European defence industry will not be to build up its capacity to produce the drone technology of the Russo-Ukrainian War. It will be to build the capacity to both develop new and battlefield-relevant drone technology *and* to rapidly bring that technology to the battlefield *en masse*. We are not concerned with the shape of the future of war. We are concerned with the *development* of the technology that will be used to fight it and the dynamics in the *industry* that will supply it.

In this spirit, our findings build on those advanced by Braunerhjelm & Brychko (2025a, 2025b) and Matlack et al (2025. Independently of each other, both studies come to the conclusion that the growth of Ukraine's drone industry as one defined by speed, scale and urgency. Both studies also highlight the innovative capacity of the Ukrainian frontline soldiers and the personally felt urgency of innovating, as well as extensive collaboration with outside partners in industry and volunteers in civil society. Our findings broadly align with these observations and provide no grounds for objecting in principle to the policy recommendations that these studies advance. What our analysis adds is a detailed understanding of the dynamics that allow frontline soldiers to innovate and to do so at the scale observed, as well as of the organization of drone industry firms as it relates to interacting with innovative frontline soldiers and specializing in forms of innovation that support their innovative efforts. As such, the recommendations that we advance can be read as extending those of especially Braunerhjelm & Brychko (2025b), emphasizing specifically how one might organize within military organizations to enhance innovation and diffusion, how one might one organize and support collaboration between military organizations and industry, and what kind of industrial specializations might allow for *both* rapid adaptive innovation and large-scale efficient production.

3. User innovation and producer-user interaction

Our analysis is grounded in user innovation theory. To say that an innovation is a user innovation is to say something about the functional source of the innovation, i.e. the relationship be-tween the innovator and the innovation and more specifically the innovator's motive for developing the innovation. The prevailing paradigm in innovation management research has since foundational work in the discipline been that innovations are developed by producers (Baldwin & von Hippel, 2011). In this producer-innovation model, the innovator expects to benefit from the innovation by producing and selling it on to others. User innovation, on the other hand, describes a situation where the innovator develops an innovation to use it themself, i.e. where the innovator's expected benefit of the innovation comes not from the sale of the innovation, but from the use of it.

3.1 The occurrence of user innovation in civilian and military contexts

A large body of literature has convincingly documented that user innovation occurs widely across the economy. While the earliest documentary evidence came from niche fields (e.g. Von Hippel, 1976), subsequent scholarship documented that up to a third of users in fields like open-source software, surgical equipment, and extreme sports developed innovations for their own use (for summary, see von Hippel, 2005, table 2.1). Representative surveys of firms found that up to forty percent of them developed process innovations for in-house use (i.e. as users), while representative surveys of consumers found that up to six percent of all consumers develop innovations for their own use (for summary, see de Jong, 2016, table 4.1). To provide a sense of scale to that latter number: a representative survey conducted in the UK (von Hippel et al, 2012) found that product users' investment in user innovation exceeded the total consumer product R&D of all firms in the UK by 40 percent (i.e. user innovation investment was 1.4 times producer innovation investment in the category).

Recent years have provided increasingly compelling 'existence proof' of user innovation in military contexts. Historical analyses of the US Navy 1900-1902 (Morison, 1966), of the Ger-man Army 1916-1918 (Foley, 2012), and of the British campaign in Afghanistan 2006-2009 (Farrell, 2010) all provide evidence of ('frontline') innovation, motivated by the expected benefits of using innovations directly. Case studies of specific innovations, such as flight planning software (Lindsay, 2010) and gun trucks (Kollars, 2012), also highlight the role of users in military innovation and adaptation writ large. The problem with these studies, alas, is that they do not provide any details on the empirical scope of user innovation: they show that it exists, but not whether it is particularly common. The best, but still very limited, evidence that we have on the empirical scope of user innovation in military contexts comes from Hartmann & Hartmann's (2023) ethnography of innovation hiding. Collecting innovation histories in two military company-size units, they

identified 51 user-developed innovations in one unit and 19 in another, suggesting that between 1 in 3 and 1 in 8 soldiers had engaged in user innovation.[1]

3.2 The causes and nature of user innovation

In non-military and military contexts alike, it is clear that user innovation happens primarily in response to the innovator's own needs (von Hippel, 2005; see also Hartmann & Hartmann, 2023): individuals experience a problem directly, recognize that no solution exists to solve that problem, and innovate to solve that problem. Users frequently have heterogenous needs (Franke & Von Hippel, 2003) and may decide to innovate to address those needs rather than settling for 'good enough' solutions developed by others. Also, when users are ahead of market trends, they may both experience more heterogenous needs and experience stronger incentives to innovate to address them, leading such users (termed 'lead users') to innovate at higher rates than non-lead users and to develop more valuable innovations (Von Hippel, 1986; Franke & von Hippel, 2003). This has led to speculation that crises, by intensifying the need for new solutions, might increase the extent and value of user innovation (e.g. Hartmann & Hartmann, 2020) by, as it were, turning more users into lead users.

The user innovation process is characterized by several other noteworthy dynamics. We know that users tend to play, relative to producers, to play expansive roles in developing non-product innovations: they disproportionately develop the 'behavioral' innovations that complement and make useful product innovations (e.g. Baldwin et al, 2006; Hienerth, 2016; von Hippel & Cann, 2021), with recent evidence suggesting that the performance effects of behavioral innovations vastly exceed those of product innovations (Von Hippel et al, 2024). We also know that users tend to innovate based on in-depth understanding of their own problems and locally available solution knowledge (von Hippel, 1994, Lüthje et al, 2005; von Hippel & von Krogh, 2016), and it has been argued that they may also rely on locally available (i.e. near-costless) material resources (Hartmann & Hartmann, 2023). Some have argued that users may in fact be over-relying on local knowledge and material resources and underinvesting in the development of innovations (Svensson & Hartmann, 2018; see also von Hippel & Katz, 2002). Finally, users tend to freely reveal their innovations to other users and producers (von Hippel & von Krogh, 2006), provided there are not significant costs associated with doing so (de Jong et al, 2015). Military contexts, Hartmann & Hartmann (2023) argue, tend to represent contexts where there are significant potential costs of revealing, leading many innovations to be subject to deliberate hiding and, by implication, creating an under-diffusion of innovation. However, akin to how crises can motivate more and higher-quality innovation by users, crises may also increase the incentives for, and reduce the potential costs of, revealing innovations even within bureaucratic systems (Hartmann & Hartmann, 2020).

The increasing recognition of users' innovative contributions has prompted extensive discussion of the relationship between user innovators and producer firms. There are two conventional accounts of that relationship. One posits that users dominate innovative

[1] *Unpublished* representative surveys of enlisted personnel conducted in connection with that ethnographic suggested that 88 percent of soldiers in one unit and 91 in another had modified or developed solutions for their own use. In the respective units, 33 and 41 percent of soldiers were classed as having developed function-ally novel innovations.

activities in the early stages of industry development and that producers grow in importance as the industry matures and product standards settle (e.g. Baldwin et al, 2006). In that model, producers are assumed to have relatively limited interaction with users and to enter the industry only once uncertainty around technologies and markets have been reduced. The alternative account suggests that firms can organize to collaborate with users and user communities, shifting innovative labor towards users and specializing in those activities where producers have comparative advantages (e.g. Baldwin & von Hippel, 2011; von Hippel, 2017; Gambardella et al, 2016). There are, however, widely recognized difficulties in doing so. Even as technological change makes it economically viable for users to innovate on their own (Baldwin & von Hippel, 2011) and for firms to collaborate with users (e.g. Altman et al, 2014), users' knowledge of their needs and the systems-of-use into which innovations must mesh is likely to be difficult to transfer to firms (von Hippel, 1994) and firms will often need to invest considerably in building up the capacity to 'absorb' this kind of information (Schweisfurth & Raasch, 2018; see also Cohen & Levinthal, 1990). Absent such absorptive capacity, firms may struggle to recognize, assimilate and apply the relevant knowledge about user needs and innovations.

4. Methods

We base our analysis primarily on secondary sources in the form of openly available news coverage. While this data source does not provide direct access to the 'facts on the ground' and forces us to work with more shallow data, it does have several advantages for our purpose. Journalistic coverage of the Russo-Ukrainian war has been very extensive, with journalists from Western media covering events across multiple fronts and over time, allowing for broader and longer-term empirical access than would be achievable with even a large research team. Moreover, journalists often (but not always) have better access to both units and individuals than academic researchers. As such, we are trading off direct access and thick data against broad insight. While that trade-off will not be meaningful for all research purposes, it is meaningful given our specific interest: we want to understand not the micro-processes of how innovations are developed, but broad trends in where innovation occurs and how different actors in the ecosystem surrounding innovations interact. It is well-accepted practice to base analyses of this nature on these kinds of sources (e.g. Rosa et al, 1990; Navis & Glynn, 2010; Raffaeli, 2019; Krabbe & Grodal, 2023; Hsu & Grodal, 2020).

4.1 Data sources

To compile our dataset, we used the Factiva database to search for relevant articles from The Financial Times, New York Times, and Washington Post. In addition, we searched for articles in The Economist, Foreign Policy, Foreign Affairs, and Wired, and the websites of Forbes and Associated Press In these outlets, we identified all articles published between January 1, 2022 (i.e. prior to the Russian invasion of Ukraine) and July 1, 2025, that contained both the words Ukraine and drone. We then manually sorted this dataset to identify articles that were most relevant to our focus on the innovation process. As one might expect, most articles were not directly relevant: the broadness of the search terms implied that many articles reported on the specific battles and the progress of the war in general, while a substantial subset dealt in greater detail with the use of drones on the battlefield. A smaller substantial subset dealt with the implications for 'the future of war', allowing us to reduce the corpus of material that we subject to further analysis.

Furthermore, we identified reports and whitepapers from Ukrainian ministries, industry, and thinktanks. This included reports written by insiders with privileged access to Ukrainian strategies about the incorporation and adaptation of commercial technologies (e.g. Bondar, 2024. 2025; Watling & Reynolds, 2025; Bilousova et al, 2024). Among other sources, these reports draw on fieldwork and in-depth interviews conducted throughout 2024 and 2025 with Ukrainian Armed Forces personnel, including various brigades, frontline units, Commands, the security services, and General Staff, in additions to MOD officials, defense startup founders, commercial drone manufacturers, defense companies, and venture capital funds

This study furthermore incorporates peer-reviewed work, trip reports from researchers attending Ukrainian defense industry events, and policy briefs with analysis of news reporting – a common approach for a topic as challenging to gain access to as this (e.g. Probasco, 2024). These sources provide an overview of the landscape of innovation from

frontline units to the strategic discussions taking place within the political and military leadership, while adding important local contextual insights from being embedded within the Ukrainian ecosystem. As such, this perspective grounds the analysis in both practitioner experiences and comparative institutional context and enables triangulation between different reports to substantiate findings from across the Ukrainian development ecosystem.

Like many other studies of drones in the Russo-Ukrainian War, we also drew on analyses published on widely-read specialist blogs. Relevant websites and blogs were identified throughout 2023-2025 based on posts related to weapons development in Ukraine with an emphasis on drones. These include War on the Rocks, Inside Unmanned Systems, Defence-blog, Defense One, Militarnyi and Intelligence Online. These serve as practitioner forums that provide examples of specific adaptations and insight into discussions of persistent challenges within both technical and organizational spheres. Compared to more high-level summative analytical reporting, these sources often provide concrete examples of new technology and tactics, including pictures and descriptions of setting, allowing these to be roughly dated and located, indicating development timelines and innovation actors. These are intended to supplement and illustrate key trends and dynamics but are not a systematic analysis of all publicly available examples of adaptations.

4.2 Analysis

The focused dataset and the corpus of identified reports, blogposts, whitepapers and published studies was abductively analyzed (Timmermans & Tavory, 2012; Sætre & Van de Ven, 2021). We began by manually reading each source, looking for patterns around the types, source, and process of innovations. Based on these emergent patterns, we engaged more deeply with the user innovation literature, specifically those parts of it that deal with systems-of-use, users' in-novation niches, the determinants of users' innovative capacities, and the relationships between users and producer-firms. We then used the concepts and ideas from this literature to revisit the empirical material in a more focused manner, comparing and contrasting theoretical and empirical dynamics in order to tease out how the rapid development of drone technology could be understood in terms of theories of user innovation and how dynamics in the Russo-Ukrainian War differed from theoretical expectations. As ideas emerged through this constant comparative process, we made notes of them and then 'tested' them against the remaining material in order to abandon, nuance and refine, or further pursue them. Based on this analysis, we ultimately focused on the role and nature of user innovation, the user-to-user and user-to-producer communication dynamics, and the absorptive capacity and specialization of producer firms.

At the outset, it is worth stating the obvious: In war, truth is the first casualty. When we rely on media reports and analyses of the kind outlined above, we are relying on the reports of journalists, commentators and researchers who have been allowed to report from a context that we should necessarily assume is information-controlled, and those journalists are therefore likely to have a distorted perception of realities on the grounded. The military forces being covered have a vested interest in presenting themselves in a

positive light and are likely to provide outside observers preferential access to contexts that showcase what are perceived as positive stories. Moreover, given the nature of the conflict and its geopolitical context, the Ukrainian forces up-on which we focus are likely to be presented in a broadly positive light in many Western media outlets. While this would inevitably be true, we became particularly sensitive to this positive representation in accounts about the "MacGyverism" and ingenuity of the Ukrainian forces, the dynamism and bottom-up innovativeness of the Ukrainian defence industry, and the future prospects of this industry as it pertains to supplying especially European customers. Such accounts could easily be read as aligning Ukraine with American and European discourses and positioning it as the anti-thesis to a slow, lumbering, top-down military bureaucracy (in the sources, this is how Russia tends to be portrayed). When we rely on whitepapers and reports, we face simi-lar challenges: while these documents serve many functions, one of their obvious functions is to communicate to allies and audiences in the West not only the 'truth', but also an image of Ukraine as aligned with Western discourses and values.

We dealt with this problem in our data by mobilizing the hermeneutic approach often associated with historical research. While there is an expansive literature on this approach, Kipping et al (2014) summarize it as comprising three steps. First, we engaged in source criticism. Aside from being aware of the validity issues outlined in the prior paragraph, we prioritized accounts that were close to the event in space and time, such that we prioritized direct reporting and interviews over reporting based on issued statements, reporting soon after events over more temporally distant reporting, and reporting with transparent sources over ones with opaque sources. Moreover, we triangulated between sources, such that we compared coverage of events across multiple sources and sought out variation in interpretations between them, paying particular attention to "dissonant data". Finally, we allowed our own understanding to emerge by oscillating between the specific data and the broader context in which that statement was made, with each additional data point adding to our understanding of the context, and our evolving under-standing of the context allowing for a deeper understanding of the specific statement.

Using this method included an evolving understanding of what we might term 'trends in reporting': as we examined the collected data, it became evident that reporting at times tended to con-verge around particular tropes, and that these tropes would then dominate before being replaced by new ones. We understand this tendency as reflecting that journalists and editors tend to focus their attention on 'hot' issues, amplifying their importance relative to that of others. Taken together, this is to say that while we are obviously too close to the phenomenon under study to approach it with the detachment that comes with the passage of time, and have too homogenous data to engage in depth with divergent observations (from e.g. social media accounts or soldiers' diaries), the hermeneutic approach is nonetheless a helpful starting point for engaging with the data in a reflexive, albeit imperfect, manner.

A further methodological problem is that our sources are, almost by definition, biased by the absence of failed innovations. It is safe to assume that for every innovation described in our data, there are multiple innovations that were unsuccessful when brought to the battlefield, and therefore never reported on. Moreover, for every innovation brought to the battlefield, there are likely to have been multiple failed efforts to develop innovations. What this does is to create in our data an exaggerated sense of the efficacy of innovations and much too positive sense of how capable, safe, and efficient users are in their innovation efforts. We have tried to take account of this in our treatment of the empirical material, but given the uncertainties associated with what gets reported and the difficulties of assessing the extent of the unreported efforts, this remains a fundamental problem in our data.

5. Findings

In the immediate aftermath of the Russian invasion of Ukraine, a highly distributed innovation process emerged around the use of drones on the Ukrainian side. Instead of relying exclusively on issued equipment and their associated military practices, soldiers adopted 'commercial, off-the-shelf' (COTS) hobby drones that they themselves bought and had sent to their frontline positions for military use. This use included reconnaissance, situational awareness and artillery observation and guidance but quickly expanded to also encompass using drones for more offensive activities, e.g. to drop small explosives and hand grenades into the open turrets of op-ponent tanks. For this expanded use, COTS drones had to be modified and augmented with modules that expanded their functionality (e.g. an attachment that allowed for carrying and re-mote-controlled releasing of a hand grenade). Some of these modifications soldiers would make themselves, while others would be produced by private citizens and associations using soldiers' specifications, open-source designs, and 3D printing equipment. In several cases, such private efforts to support frontline troops were supported by crowdsourced funding. These activities, often labelled 'MacGyverist' in reference to the ingenuity of the eponymous protagonist of the tv-show MacGyver, were broadly accepted and encouraged by the Ukrainian military and practices and innovations appeared to diffuse widely within the Ukrainian forces.

While the image of Ukrainian ingenuity and 'agility' that these practices may convey has persisted in reporting and analyses around the conflict, the remainder of our findings will dwell on subsequent developments and how they might be understood. To do so, we first discuss the forms of drone innovation that have occurred and the role of user innovators in then. Then, we explore the characteristics of innovating drone users and how Ukrainian military units organize for drone innovation. Finally, we describe the communication practices within the Ukrainian military, and across the boundaries of military units, that allow for rapid sharing of problem knowledge and diffusion of innovations, as well as the characteristics of producer organizations that appear particularly well-positioned to absorb and engage with such knowledge and innovations.

5.1 The forms of drone innovation: Technologies, components and systems-of-use

While both Ukrainian and Russian forces had access to drones at the beginning of the conflict, there has been a considerable expansion of the varieties of drones used and considerable developments in their performance. Initially, both sides used (comparatively expensive) military 'fixed wing' drones for forward observation, direction and adjustment of artillery fire, and cueing of strike systems. In contrast, the soldier-led adoption of drones in the early stages of the conflict were of commercially available quadcopters that were smaller, had shorter range, and could be used for a broader range of purposes. Late 2022 saw the introduction of 'one-way attack' ("kamikaze") drones that, like the military drones of the early conflict, were of the fixed-wing variety. Unlike those early drones, one-way attack (OWA) drones were often 'loitering munitions', used for bombing attacks, and not reusable. In 2023, small and fast 'first person view' (FPV) quadcopter drones that were piloted using VR-headsets and could be used for both reconnaissance and offensive operations, including against moving targets and in

confined spaces, began to appear on the battlefield. Since then, a variety of styles and sizes of drones, including maritime and ground-based drones, have been deployed and are used in a vast range of battlefield roles. Concurrently, drones across the spectrum of use have improved their range, speed, carrying capacity, resistance to jamming, maneuverability, and ability to operate autonomously. While drones remain "finicky, unreliable, hard to use, and susceptible to electronic interference"[2] and "[w]ind, rain, snow, and fog all mean a drone cannot fly" (ibid), it is still clear that today's drones are much more capable than at the beginning of the war.

While a considerable share of the improvement in drones results from the introduction of wholly new technological systems (FPV drones, OWA drones, maritime drones, etc.) or new generations of technologies, much of it also clearly stems from improvement at the level of components or modules. A drone is composed of sub-systems that, in aggregate, allow it to perform at a certain level, including (often, but not always) electric motors, batteries, controllers, cameras, software, video transmitters, etc. The continuous "updating and enhancing of components such as antennas, remote controls, and batteries", notes the Modern War Institute, are crucial to ensuring the effectiveness of drones used in the frontline.[3] They continue: "By implementing software updates, technicians can make drones less detectable to enemy systems. This includes modifications that increase drone ranges and altitudes and further adaptations that remove features that transmit identification or locations information, which helps to minimize the risk of interception." A drone developer describes what such sub-system developments can entail: "Playing with the motors and the propellers, you can make [an FPV] run with velocity of 200 [km/h]. So it's easy to shoot down [other drones]."[4] By some reports, there is a "flurry of tweaks" to drone designs and radio frequences have occurred all along the frontline.[5]

Moreover, performance can be enhanced through modular additions. Drones can be fitted with e.g. firearms or attachments that allow them to inflict more, or more targeted, damage, or with e.g. additional antennas that allow them to avoid jamming and thus perform under more adverse conditions. Consider, for instance, 'dragon drones' as described in one New York Times re-portage: "Capt. Viacheslav, 30, the commander of the 68th Separate Jaeger Brigade's strike drone company known as "Dovbush's Hornets".[struggled to drive enemy forces out of cover].[6] But they could not do so, he said in an interview last month. So they gave a new weapon a newer twist, attaching thermite-spewing canisters to drones and creating a weapon capable of spitting out molten metal that burns at 4,400 degrees Fahrenheit. Soldiers call them "dragon drones." Thermite -- which was developed a century ago to weld railroad tracks -- is a mixture of aluminum and iron oxide […] has been used primarily in artillery shells and hand grenades. Now it is being attached to drones that sweep over Russian defensive positions, raining burning metal over the enemy before crashing. The flames ignite the vegetation that Russian troops use for cover and burn it out, exposing them and their

[2] *I Fought in Ukraine and Here's Why FPV Drones Kind of Suck*, 26-06-2025, War on the Rocks.
[3] *Innovating Under Fire: Lessons from Ukraine's Frontline Drone Workshops*, 25-03-2025, Modern War Institute.
[4] *Beyond the drone line: Lessons from the drone war in Ukraine*, 03-06-2025, European Security & Defence
[5] *Kyiv's Budget Drones Prove Their Value in a Billion-Dollar War*, 24-09-2023, The New York Times.
[6] *Fire-Breathing 'Dragon Drones' Are Flying Into Battle*, 13-10-2024, The New York Times.

equipment to direct attack." Here, innovation lies not in improvements to the drone itself, but in the modular additions to it.

As parts of systems-of-use, and not just as technological systems, drones have also clearly been complemented by behavioral innovations, i.e. techniques and practices for deploying drones. Consider, for instance, using FPV drones for attacking enemy trenches. Doing so will involve piloting a drone to the required location and then releasing the munition to hit the trench in question, which will obviously carry the risk of missing the mark. Some Ukrainian units, how-ever, developed techniques for "dive bombing" their drones towards the target, flying rapidly towards it and releasing its explosive payload at close range. This technique increased the effectiveness of the drone, without changing the drone itself. In other cases, a change in the drone itself makes possible such behavioral innovations. In a reportage from Forbes, a prior volunteer in a Ukrainian drone unit describes what becomes possible when drones are controlled through a fiber-optic connection, as opposed to a radio connection: "The absence of an energy-guzzling radio transmitter can extend battery life and even allow for some innovative tactics, such as landing the drone next to a road and waiting for several hours until a vehicle passes by" and then chasing down and engaging that vehicle.[7] Tactics have also emerged around intercepting other drones,[8] using smaller drones to escort larger ones, and engaging in aerial drone-on-drone dogfights, and frontline units are implementing those tactics into their training procedures.[9]

One form of innovation that has played a key role in the conflict falls between the technological and the behavioral, taking the form of what might be termed repurposing, or 'affordance discovery', i.e. discovering potential uses for (or affordances of) particular drones. Three examples are particularly illustrative here: the use of drones originally designed for photography as reconnaissance drones, the use of FPV drones for 'kamikaze operations' and the use of agricultural drones for bombing operations. Ukraine's initial use of COTS drones for reconnaissance came from a recognition that these drones, which soldiers might have used in their civilian lives (e.g. for wedding photography), could also serve to provide frontline units with a much-improved view of the battlefield and of enemy movements.[10] The use of FPV drones for kamikaze attacks came from a recognition that the speed and maneuverability of such drones, otherwise used for civilian drone racing, could make them function akin to small guided missiles.[11] The repurposing of agricultural drones came from the insight that such drones, otherwise used to carry pesticides and spray fields, also had the capacity to carry 20-kg bombs that would be far too heavy for the smaller, more common, quadcopters.[12]

[7] How Have Ukrainian Drones Beaten Russian Jammers — And Will It Last?, 09-08-2023, Forbes.
[8] I Fought in Ukraine and Here's Why FPV Drones Kind of Suck, 26-06-2025, War on the Rocks.
[9] Interceptors And Escorts: Drone Tactics In Ukraine Are Evolving Fast, 16-04-2024, Forbes.
[10] From weddings to war: Ukrainian photographers turn drone operators in fight against Russia, 30-09-2023, The Telegraph.
[11] How racing drones are used as improvised missiles in Ukraine, 24-03-2023, The Economist.
[12] Strikes at 60 km, mining of rear areas and air evacuation of the wounded. All about our drone bombers that scare the Russians, 14-10-2025, Oboronka,

5.2 The sources of drone innovation: Producers and users

The war has seen a dramatic expansion of the Ukrainian defence industry. According to a re-port published jointly by the Ukrainian Institute for the Future and the Ukrainian Council for Defence Industry in early 2025, the industry consists of more than 800 private and state-owned enterprises at the end of 2024 (up from ca. 300 at the start of year), employing more than 300,000 people (up from 70,000). The industry increased production capacity sixfold in 2024 (relative to 2023) and produced approx. US$10 billion worth of arms (up from US$3 in 2023; expected to reach US$30 in 2025). This production included 1.5 million FPV drones, and pro-duction covers 96% of all drones used by Ukrainian forces. Also in 2024, more than 500 new types of weapons and equipment were approved for operations by Ukraine's domestic defence industry. This growth readily invites the interpretation that defence industry producers might be the primary drivers of innovation. That, however, would be misleading.

It is clear from our sources that both producers and users originate drone-related innovation. When our sources report on new forms of drones, some are described as developed by users and others by producers. Reporting on the development of an unmanned ground vehicle (UGV), the Wall Street Journal describes an example of user-led development. "Ukrainian Army Private Oleksiy Yelin of the 93rd Brigade controls a land drone he designed approximately 16 miles from the front line in Ukraine's eastern Donetsk region. The drone can travel up to 6km (approximately 3.7 miles) depending on the terrain and can be used to drop mines or de-liver ammunition to soldiers based on design modifications. "Sea drones like the Magura 5 (for offensive operations) or Sea Baby (for mine-laying), by contrast, were developed by HUR and SBU, respectively the Ukrainian Main Directorate of Intelligence and the Ukrainian Security Service, i.e. user-organizations.[13] Drones like the Sting interceptor drones, designed to take down enemy OWA drones, appear to often be developed by producer-firms, in this case the non-profit firm Wild Hornets.[14]

Many of the sub-components that make up drones are procured through the open market (e.g. rotors, batteries, cameras, sensors, etc.) and the ones that are procured in this manner tend to be developed and improved upon by producers. Users, however, appear to engage in considerable experimentation with reconfiguration of such standard components. According to one New York Times report, "Cobbled together from hobby drones, consumer electronics and computer gaming gear, handmade attack drones like [a particular configuration] have emerged as one of the deadliest and most widespread innovations in more than 14 months of warfare in Ukraine.[15] Along the front line, drones extend the reach of soldiers, who can fly them with pinpoint accuracy to drop hand grenades into enemy trenches or bunkers, or fly into targets to blow up on impact. Self-destructing drones, in particular, are easily constructed, and thousands of soldiers on both sides now have experience building them from commonly available parts -- though the Ukrainians say they use such weapons more frequently than their Russian opponents".

[13] Ukraine, With No Warships, Uses Innovation to Thwart Russia's Navy, 13-11-2023, The New York Times.
[14] Adaptation at Hyper Speed, 14-06-2023, Inside Unmanned Systems.
[15] Ukraine's Attack Drones: Homemade, Cheap and Lethal, 09-05-2023, The New York Times.

Many of the modular innovations that extend the utility of drones into new domains appear to be developed by users. There are numerous reports of how the designs for the 'claws' that were used to hold and drop grenades and small explosives were developed by soldiers along the frontline.[16] The aforementioned dragon drones, for instance, were developed by frontline soldiers in a drone strike unit. In another unit, a soldier disassembled US-provided cluster munitions and connected the bomblets from those munitions to a drone, thus creating an anti-infantry drone. Reporting on a sapper unit, Financial Times writes: "The sappers work with a huge range of ammunition, adapting them to attach to different types of drones. […] [Around them] are parts of an RPG-7 rocket launcher, some thermobaric vacuum bombs and other grenades [used to modify drones]."[17] Another report presents the following narrative, highlighting how soldiers develop and self-produce modifications for a standard drone that, in this case, allow for a non-remote triggering of an explosive payload:

> "Driving through the snow blanketed woods next to a frozen lake I see the first sign of life, smoke rising from the chimney of an old wood hunting lodge. Inside, I meet a group of Ukrainian soldiers, some cooking, some cleaning, and others chopping wood, taking a well-deserved break from the front.
>
> In the wood-paneled dining room, with the glass eyes of squirrels, deer, and other critters peering down from their frozen poses, past the pictures of club members of bygone years showing off their trophies, stands a well-lit but worn-out desk. A bright desk light spotlight-ing a soldering station, constantly at work, assembling the next iteration of first-person-view (FPV) drones for when the unit goes back to the front.
>
> But these drones look different, armed with two thickly curled wires that resemble horns in front, a manual trigger in lieu of a remote, meant to close a circuit when the drone slams in-to its target at speed, triggering an explosive blast. Another small change in a war charac-terized by innovation."[18]

Other modifications and modules are not developed by users, but in direct response to user needs. According to a report from the Modern War Institute, "Drone workshops" within Ukrainian battalions staffed by technical specialists "serve as the forward-most resource for addressing technical challenges that could hamper UAV operations", providing frontline operators with the support to develop ideas into functioning solutions. "Any technical issues encountered by remote operators can be communicated back to the workshops, where engineers work to devise solutions that enhance the operational capabilities of the UAVs. For example, suppose a Russian electronic warfare system is actively jamming a particular frequency along the front line. Instead of going through a lengthy bureaucratic process, these operators can mitigate these problems in-house, often changing tactics and frequencies in hours, not days or weeks. By be-ing embedded within the battalion structure, these workshops demonstrate exceptional

[16] Ukraine's Drone Army Takes Bites Out of Bigger Opponent, 11-09-2023, The Wall Street Journal.
[17] Sketches of the war in Ukraine: dispatch from the Russian border, 05-10-2024, Financial Times.
[18] Ukraine's Rapid Innovation Cycle is Changing the Future of War, 14-04-2024, The Cipher Brief.

agility, recalibrating their focus based on the immediate needs of combat units in the field", the report continues.[19] These drone workshops do not replace the innovations undertaken by volunteers during the early conflict but rather bring a similar capacity for responding to user needs inside the military units. It is also within these workshops, it appears, that many experiments with modifying components, or using new ones, in existing drone systems are done. In such situations, producer-developed drones can be used as platforms that users innovate 'on top of', rather than as stand-alone systems.

Frontline users also appear to originate most of the behavioral innovations that we see described in our empirical material. We say 'appear' because the source of behavioral innovations tends to be described very cursorily, but in those situations where the source of innovation can be inferred, users are almost always the source. The evolution of interceptor drones illustrates. As reported by European Security & Defence, "To help counter the almost ubiquitous Russian reconnaissance drones… Ukrainian units began engaging them kinetically with FPV drones. Video footage that shows an FPV approaching a class 2 fixed-wing drone from behind is now a relatively common sight on the social media channels of the Ukrainian MoD. The tactic expanded, and videos soon emerged of small class one drones physically crashing into each other to try and bring the adversary drone down." Put differently, the notion that smaller drones could be used to intercept larger and more costly ones originated amongst frontline users, before, as subsequently happened, the government initiative Brave1 began to apply the notion in developing drones specifically designed for intercepting Russian OWA drones. The emergent uses of drones as a means of let Russian soldiers surrender, as reported by the New York Times, can similarly be thought of as a behavioral innovation.[20] Another New York Times reportage de-scribes behavioral innovations in the field of drone-related electronic warfare: "Once the purview of trained experts, the technologies have spread to frontline infantry troops. Ukrainian drone pilots said they constantly fine-tuned their methods to parry the invisible attacks."[21]

5.3 Contextualizing the innovative user: Sophistication and concentration

While the descriptions of user innovation above invite the interpretation that innovative users are distributed throughout the Ukrainian forces and that all Ukrainian soldiers should be through of as user innovators, this interpretation would be erroneous. Many of the innovating users that we see described in our sources have civilian backgrounds in technical fields, reflecting prior findings that especially young men with technical education tend to be likely to engage in user innovation (Von Hippel et al, 2011). Following the Russian invasion, such individuals, who might previously have worked in the large Ukrainian software and technology industry, volunteered for, or were drafted into, the Ukrainian armed forces. One New York Times reportage illustrates, writing "Lieutenant Arutiunian, who uses the military call sign Doc -- a reference to the doctorate in data mining he holds from Kyiv Polytechnic -- commands four teams in the unmanned aerial vehicle service of the Ukrainian Volunteer Army, operating on the southern front.

[19] Innovating Under Fire: Lessons from Ukraine's Frontline Drone Workshops, 25-03-2025, Modern War Institute.

[20] A 21st Century War: Russians Can Give Up To Ukrainian Drones, 20-12-2022, The New York Times.

[21] Invisible Battle Is Being Fought Above Ukraine, 20-11-2023, The New York Times.

They deploy a variety of propeller-driven drones and planes to track Russian forces for the Ukrainian military and are constantly adjusting tactics and equipment to evade Russian interceptors."[22] We see similar references to civilian backgrounds in e.g. software development, telecom engineering, nuclear engineering and IT project management throughout our data. In this connection, it is worth noting the Ukrainian software industry, long a location for outsourcing from EU and US, according to the Ukrainian National Bank, was growing rap-idly and exporting in excess of $5 billion prior to the war's beginning.[23]

The software industry is not the only source for technologically sophisticated soldiers. References to soldiers with backgrounds as drone hobbyists are common throughout our sources, and such hobbyists-turned-soldiers are frequently credited with discovering ways to repurpose technologies, with behavioral innovations, and with making modifications that improve the performance of drones. Soldiers with strong backgrounds in video games are also mentioned as originating especially behavioral innovations, e.g. around flight technique and use of drones in confined quarters. More rarely, we see references to soldiers with a background in Ukraine's defense industries that prior to the war provided ca. 20 percent of Ukrainian military equipment. Rarer still, we see references to soldiers with a background in Ukraine's agricultural drone industry. There are, in other words, multiple ways in which users can be technologically prepared for engaging in drone innovation and while such technological sophistication is far from a pre-requisite for innovating, it is noteworthy how often innovative users are reported as having such a background.

It would also be misleading to assume that innovative users are evenly distributed across the Ukrainian armed forces. On the contrary, they tend to concentrate in specialized drone companies or battalions, organized as part of every army brigade. "Every brigade in the Ukrainian army has a drone unit, while some brigades also have specialized workshops", writes one re-port.[24] Aerial Strike Units were implemented across the armed forces under the 'Army of Drones' initiative. Writing about specialized workshops, a report from the Modern War Institute states "The operational effectiveness of top Ukrainian drone units is deeply linked to the efficient maintenance and functionality of their UAVs. This requirement highlights the critical role of Ukrainian drone engineer workshops and electronic laboratories. These facilities function as vital centers for innovation and repair […] Drone workshops are typically integrated within the organizational structure of UAV battalions operating under Ukrainian brigades. These engineer-ing workshops serve as the forward-most resource for addressing technical challenges that could hamper UAV operations. Comprised of ten to twelve specialized Ukrainian soldiers, these units focus on UAVs' modernization and combat readiness, engaging in developing and innovating new technologies while testing existing equipment.[25] They also cultivate an atmosphere of continuous improvement,

[22] Going Behind Enemy Lines for Bird's-Eye View, 11-08-2023, The New York Times.

[23] Robots Are Entering the Ukraine Battlefield, 22-03-2024, The Wall Street Journal; How 'creative insecurity' is stimulating Ukrainian innovation, 10-08-2023, Financial Times; The growing IT sector in Ukraine, date not available, BBC.

[24] ERR in Kharkiv oblast: Every Ukrainian army brigade has its drone unit, 27-01-2025, ERR.

[25] Innovating Under Fire: Lessons from Ukraine's Frontline Drone Workshops, 25-03-2025, Modern War Institute.

essential on a rapidly evolving technological battlefield. The personnel involved are often skilled engineers or technicians, deeply familiar with drone technology, propulsion systems, sensors, and software interfaces. Their expertise encompasses various functions, including diagnostics, repairs, upgrades, and integrating new components into existing UAV platforms." Specialized units and workshops like this deliberately seek to recruit technologically sophisticated users and bring them into contexts that increase their personal need for drone-related innovations, providing, as it were, access to sticky user knowledge and increasing lead-userness.

Speaking to the further concentration of user innovation, particular units within the Ukrainian forces also appear to be particularly common sources of innovation. According to a report from Ukraine Arms Monitor, “Some units have become hubs for experimentation”, such as “Magyar’s Birds” (also known as 414th Separate Brigade), that has been amongst the most successful UAS groups within the AFU [i.e. Armed Forces of Ukraine].[26] They have been able to at-tract more skilled pilots and extra funding, creating better conditions for sustained development. In turn, this success has seen the unit’s commander being appointed as head of Ukraine’s Un-manned Systems Forces. In this function, he has been tasked with creating strategies for drone use, showing how front-line experience is flowing upwards in the organization. This further illustrates that user innovation is not necessarily equally distributed throughout the AFU, but can be fostered by selection and support. In this sense, while innovation appears to have been in principle ‘democratized’, it is in practice concentrated in ways that resemble what has previously been observed in open-source projects (e.g. Von Krogh et al, 2003).

5.4 Knowledge flows: Sharing through open platforms and unit embedding

Innovative users in the Ukrainian forces appear to engage in extensive peer-to-peer sharing of innovations. In non-wartime military organizations, such sharing might be limited as soldiers deliberately hide innovations from superiors (e.g. Hartmann & Hartmann, 2023) and diffuse innovations covertly (e.g. Lindsay, 2010). According to one analysis in Financial Times, “The issue at stake is how combatants organise [sic] themselves. The Russian military still appears to operate in a hierarchical manner — even though it has potent cyber-hacking and misinformation capabilities. The Ukrainian army, by contrast, gives decentralised [sic] teams considerable autonomy to make decisions and innovate, and soldiers communicate directly with their peers in different units.” Like peer-to-peer sharing in other contexts, such sharing frequently happens via commercial platforms like Signal, Telegram, Github (in the case of software), or via commercial video sharing services. According to one report, "many [troops] post photos and videos online to showcase how they’ve outfitted [commercial drones] for military use."[27] Another writes, “It's no secret that military units have groups in Signal: company group, platoon group, battalion group, and all commanders use it.”[28]

[26] Drone warfare in Ukraine: new unmanned strategy and FPV video detector, 11-06-2025, Ukraine's Arms Moni-tor.

[27] Ukrainian soldiers are turning consumer drones into formidable weapons of war, 08/08/2022, France24.

[28] "Large enterprises are not interested in creating a small trench electronic warfare system." Interview with engi-neer Serhiy "Flash", 15-05-2024, AIN.

Users also share innovations and user needs with producers through these same platforms. One analysis claims that "Soldiers all along the front send Telegram and Signal messages back to the factories, giving near instant feedback to the novel innovation on the next drone or software tool." Just as importantly, however, producers are also frequently embedded in frontline units allowing for direct engagement with user needs.[29] Describing the experience of one (non-Ukrainian) producer, Forbes writes: ""After the 2022 invasion, [a drone company's] drones were quickly sent into action, but [a representative of the company] says the feedback from Ukraine did not give a full idea of how the drones were performing. The only way was for the developers to go to the front and fly drones themselves. It was an eye-opening experience., "For sure, it was surprising," says [the representative]. [...] "Participation, doing those missions as the front lines, that is absolutely different compared to working in military ranges and on exercises".[30] A report from Georgetown University states: "Companies are sending their drones to pilots in Ukraine to get direct user feedback in the operating environment. Many participants agreed that there is almost no way to have an impact with new drones without visiting operators on the front lines and getting their input. Those battlefield tests are generating enormous in-sights for companies, and the companies are iterating based on what they hear". [31]

One further pathway through which producers and users interact is through training. In most contexts, training of operators of military equipment is undertaken by military organizations themselves. Given the high rate of innovation, the Ukrainian forces have increasingly shifted specialist training of drone operators to the innovative producer-firms that produce the technologies these operators will be using .[32] The drone producer Wild Hornets, as described in Forbes reporting, illustrates.[33] This company, operating (at the time of the reporting) at the leading edge of interceptor drones and bomber drones, is responsible for offering courses that allow drone pilots to use the company's drones. This reduces the time it takes for new solutions to be implemented.[34] However, it also provides a mechanism for transferring user insights to producers and creates a pathway for future contact with leading-edge users.

While there are extensive information flows between users and producers that allow for the transfer of user innovations and user insights to producers, drone producers appear to also ex-hibit a considerable capacity to absorb such need-related knowledge (Schweisfurth & Raasch, 2018). Many of the successful startups that supply Ukrainian forces are founded by current or former soldiers, i.e. user-entrepreneurs. One entrepreneur, interviewed by AP, illustrates: Fevzi Ametov, the founder of drone.ua, serves as an active soldier and is simultaneously involved in the running of his company.

[29] Ukraine's Rapid Innovation Cycle is Changing the Future of War, 14-04-2024, The Cipher Brief.
[30] Battlefield Experience And Advanced Software Build Better Drones, 18-03-2025, Forbes.
[31] The Future of Drones in Ukraine: A Report from the DIU-Brave1 Warsaw Conference, 13-11-2023, CSET.
[32] General introductory training in the most common types of drones is increasing hosted in military-certified drone schools that are used to boost national training capacity.
[33] Ukrainian Wild Hornets Co-Founder Talks About The Future Of Drone Wars, 26-03-2024, Forbes.
[34] How the next generation of Ukrainian drone pilots are being trained at UAV schools, 25-03-2025, Kyiv Independent.

Companies that are not founded by user-entrepreneurs appear to make extensive use of 'embedded users', i.e. current or former soldiers actively working for companies.[35]

Moreover, producers appear to have specialized in four distinct functions that in distinct ways interact with and enable particular forms of user innovation. One specialization is to concentrate efforts in those parts of the innovation process where scale is most rewarded. This includes the production of standardized components that users can re-combine in novel ways, or the assembly of quantifies of standardized drones that can be subject to tinkering by users to simply thrust into the numbers game on the battlefield. A second, and closely related to the first, is in the pro-duction of drones that serve as platforms upon which users can innovate, by customizing them for specific purposes or adding modules that extend their functionality. Rather than producing a large variety of drones, each tailored to a specific battlefield role, certain drone manufacturers seem to be oriented towards creating drones that users can subsequently adapt to specific purposes. Third, certain producers concentrate on producing the kind of modular add-ons that users can deploy to turn a standard drone into a custom one, when those kinds of modular add-ons cannot be self-produced by users (e.g. anti-jamming modules). Finally, one class of producers seems to concentrate on productizing user-developed behavioral innovations. When users identify a use for drones that current drones can fulfill but are poorly suited for (e.g. intercepting enemy kamikaze drones), producers might step in to create highly specialized products for that specific use case.

[35] Ukraine launches tech cluster to boost military capability, 26-04-2023, AP News.

6. Discussion

Our observations suggest that the contribution of innovative users has been central to the rapid technological development that has characterized the Russo-Ukrainian War since 2022. While certain parts of the technological system appear to be almost fully dominated by producers, users appear to be a common source of innovations at the component level (e.g. software), innovations based on the (architectural) recombination of components, and the extension of drone functionality through additions of modular innovations (e.g. weapons attachments). Moreover, we observe that users play a large role in developing behavioral innovations, often developing new ways of using and operating military drones, as well as in discovering previously unrecognized ways to utilize commercial drones for military purposes. It is hard to imagine that the Russo-Ukrainian War would have become a war of drones had it not been for the user innovation that Ukraine has engaged, thus forcing Russia into the drone technological race that has in part defined the conflict.

One way to understand the role of user innovation in the Russo-Ukrainian war is that the Ukrainian forces have been able to innovate as they have by leveraging the innovative capacity of users, in this case frontline soldiers, that might otherwise be latent or underutilized in military contexts. We know that users innovate in military organizations, but also that innovations might be under-developed, under-diffused and in some cases even abandoned because of the various constraints imposed on users' ability to develop, use and benefit from their innovations, and to diffuse them rapidly (Hartmann & Hartmann, 2023, 2025). With the onset of the Russian invasion, Ukrainian forces largely dispensed with those constraints and consequently saw that the latent capacity of frontline soldiers to innovate was more fully utilized.

The implication of this analysis would be that military organizations should 'simply' do less to stifle user innovation. This could imply giving users more discretion to openly experiment with new solutions and 'hack' old ones, encouraging more sharing of such solutions, and removing the sanctions that might otherwise be associated with such behavior. It would, in Kollars' terms, involve recognizing the (often underrecognized) value of 'mastery' – contextual, need-oriented, doing-using-related knowledge – in the military innovation process (see also Jensen et al, 2007). To ascribe the pace and scale of Ukrainian user innovation to the removal of those constraints and the ensuing triumph of user innovation would, however, be erroneous. While this 'letting rip' of user innovation was clearly a defining feature of the early conflict, it was only partly an explanation of the innovation of the early conflict. An equally important explanation of user innovation's success in the early conflict relates to the overrepresentation of potential drone innovators in the Ukrainian forces relative to what would be expected in most military organizations. Because of Ukraine's pre-2022 tech industry, agricultural drone industry, and defense industry, there existed in the population at large a capacity to engage in the kind of in-novation that we have subsequently observed. With the Russian invasion, many of these workers – who would, by most normal reasoning, rarely pursue military careers – volunteered or were drafted into the military. As such, the Ukrainian military as a whole needs to be under-stood as technology-literate in a way that is not typically the case elsewhere, meaning that the benefits of 'letting rip' user innovation are likely to be

accentuated. We cannot, in other words, straightforwardly expect similar effects of encouraging and enabling user innovation in other military contexts without similar technological preparedness.

Second, as the war progressed, the Ukrainian forces have deliberately worked to concentrate potential user innovators in high-need contexts. Rather than having technologically sophisticated users spread out across units[36], units have been created where such users are brought together and exposed to operations where they can benefit directly from innovation. Technologically sophisticated soldiers are trained as drone pilots, assembled in drone units, and thus confronted with a context of use where they engage with the technology, experiment with it, experience the benefits of innovating, and engage with other technologically sophisticated users. The principle at work here seems to be that the organizational context increases the 'lead userness' of potential innovators (von Hippel, 1986) and embeds them in a user community, increasing both the incentives to innovate for oneself, access to the innovations of others, and availability of peer support (Jeppesen & Laursen, 2009) both in their units and in broader networks of user-innovators with whom they are encouraged to exchange rapidly and with what appears to be low demands for communication security. Again, it seems reasonable to expect that other military organizations will struggle to replicate the Ukrainian pace of innovation without similar organizing and communication.

It also appears that a set of complementary developments have occurred on the producer side that have enabled and extended user innovation over the course of the conflict. For one, drone producers appear to have built up considerable capacity to 'absorb' knowledge about user in-novation (Schweisfurth & Raasch, 2018). Through embedding in frontline units, engagement with user communities (through communication platforms like Signal and Telegram) and training engagement with users, firms have increasingly organized in ways that expose them to user innovations and user needs. Second, many producer companies appear to have acquired direct user experience through embedding current or former lead users within their workforce (Schweisfurth & Raasch, 2015), or to be 'born' with user experience through user entrepreneurship (Shah & Tripsas, 2020). Such absorption-ready producers have been crucial to producing user-developed innovations that the industrial scale (Baldwin et al, 2006) that has proven to be necessary on a battlefield where drones are now so common that they are better thought of

[36] The de-centralised and largely uncoordinated experimentation that characterized the early stages of the conflict also saw faulty systems being used in critical situations, leading to high casualty rates, introduction of unvetted actors to the battlefield possibly acting as combatants, and potential violations of international legal obligations, e.g. Article 36 of Additional Protocol I of the Geneva Convention. Further, there are operational down-sides to the decentralized experimentation. "While drone innovations are rapid thanks to the direct involvement of warfighters and companies, this innovation–at best–lightly coordinated", states a report from Georgetown University's Center for Security and Emerging Technology, "That lack of coordination may contribute to the agility of the Ukrainians and faster iterations in technology, tactics, techniques, and procedures. In general, dynamic targeting (targets of opportunity or targeting by volunteers) is less coordinated than strategic targeting (done to guide the precious few artillery rounds, for example) and experimentation and operations within defined geographic areas may be more coordinated than across the entire theater of war, but it is clear that much experimentation is underway. Overall, this lack of coordination and the scarce financial resources contribute to a situation where Ukrainians have drones while Russians have drone systems."

ammunition than weapons. Third, producer firms seem to have concentrated in specific niches that in distinct ways interact with the distributed, user-centric innovation process.

Taken together, we propose that the rapid technological change that we observe in and around the Ukrainian military can be understood as the result of structurally innovation-capable and organizationally enabled users and absorption-ready and complement-oriented producers, al-lowing for what we would term ‘tight-loop user-producer interaction’. For defense policy making, this underscores that the key capacity to build up is neither a stock of drones nor the capacity to produce them quickly. Those capacities are surely important, but to engage in a drone-centric conflict defined by the kind of technological change that we observe in the Ukrainian context, the key capabilities to develop seem to be creating a sufficiently large base of sufficiently technology-literate users and a set of producer-firms that are capable of rapidly absorbing knowledge from these users and integrate it in both large-scale, low-cost production of highly standardized, but modular, products and smaller-scale, rapidly-iterated, high-specialization products. To innovate at the speed of war, this case suggests, requires three simultaneous elements. It involves enabling extensive innovation on the user side, building extensive capacity to identify and make production-ready those innovations on the producer side, and a manufacturing system with a diversity of user-supporting specializations.

7. Policy considerations

7.1 Costs and trade-offs

Even as many countries are looking to adapt to a drone-centric form of warfare, militaries around the world are both adopting drones into their operations and attempting to become capable of the kind of innovative engagement with them that has characterized the recent history of the Ukrainian Armed Forces. Based on the present analysis, it is somewhat of an open question whether the latter goal can and should be realized, especially in countries not faced with an existential threat to their sovereignty: Even if the innovation dynamics could be replicated, it is not obvious that other countries will be willing to bear the costs and trade-offs of doing so. Put slightly differently, our analysis makes clear that the costs (both monetary and non-monetary) of doing what the Ukrainian forces are doing are very substantial.

It is evident, for instance, that the Ukrainian forces have adopted communication practices with a level of operational security that many other military forces would (and rightly should) be uneasy with, just as it is evident that the reliance on widespread innovation across the military frontline create challenges of coordinating across, and ensuring compatibility between, techno-logical systems that may not be desirable for all countries, including especially countries whose defense depends on alliances with high levels of international coordination and standardization. The proximity of producers to military units, as well as the discretion afforded to Ukrainian military commanders, might also create a range of problems around governance and corruption risks that are non-trivial to handle. Furthermore, it is clear that Ukraine's deployment of techno-logically sophisticated users to the frontlines of the conflict have consequences. In any economy, such workers are scarce and there are opportunity costs of their deployment: when at the front, they are not contributing in other parts of the economy, including in sectors that would also be directly relevant to a war effort specifically and to the economy at large (see Gross & Sampat (2021) for an extended discussion). Certainly, there might be synergies between front-line service and contributions in the innovation economy, but those cannot simply be taken for granted (see Luttwak & Shamir (2023) for a discussion of innovation and entrepreneurship by veterans of the IDF).

7.2 Deeper engagement with the innovative capacity of military frontline users

These reservations notwithstanding, our observations suggest a range of possible paths that merit practical consideration. Most obviously, the Ukrainian case suggests the need for a much deeper engagement with the innovative capacity of military frontline users. Research has suggested that this innovation capacity has existed but also tends to be underleveraged (e.g. Hartmann & Hartmann, 2023). The Ukrainian case illuminates how military organizations could organize to more effectively leverage it: provide frontline innovators with more expanded rights to modify and experiment with equipment, encourage diffusion of innovations within and across military units, loosen requirements for force-wide standardization, devolve procurement responsibilities, and allow for decentralized interaction with industry actors. In slightly more abstract terms, leveraging the innovative capacity of frontline requires a softening of bureaucratic processes and a greater tolerance for variation and emergence.

Barring such cultural change, a more minimalist approach to leveraging users' innovative capacity can be realized through military procurement. When military organizations acquire new material, it is often in the form of integrated systems: a weapon system, for instance, might be acquired and implemented, at which point the users of the weapons are expected to use and maintain them in prescribed ways. A different approach might involve acquiring platforms that are not fully integrated, but designed around principles of modularity (e.g. Frandsen, 2017) where certain components are standardized, others are interchangeable, and yet others allow for user modifications and follow-on innovation. This would, in effect, allow for shifting innovation tasks away from being solely the preserve of producers, and allow for a more user-active innovation process (e.g. von Hippel, 1990, 2001).

It would, however, be unreasonable to expect that cultural change and a shift towards equipment-as-platforms alone would allow for the kind of user innovation that we have observed in the Ukrainian Armed Forces. An equally necessary condition is for widespread innovation is the technological literacy of those forces. To build such literacy, there are at least three options. One is to organize specialized 'drone workshops' at the battalion and brigade level that can support users in repairing, experimenting with, and modifying drones (see Svensson & Hartmann (2018) for an analysis of such innovation support in a healthcare setting). Akin to makerspaces, such workshops might provide frontline users with opportunities to realize innovative ideas, even if they themselves do not possess the technological literacy to implement them in-dependently. Another approach is to organize the training of drone operators around not just operation of drones, but also as technical training that allows operators to open the 'black box' of the technology and function simultaneously as 'drone mechanics', capable of modifying the tools that they work with. This would involve very considerable upskilling of soldiers in these combat roles. As a third option, efforts to increase technical literacy could operate 'in reverse' and take more seriously that situations in which widespread drone user would be necessary might also involve some level of mass mobilization. Under such a premise, one might attempt to increase drone-related understanding within the technically literate workforce during peace-time (as opposed to increasing the technological literacy of military drone users), such that – in the event of mobilization – individuals within the technology workforce can be channeled into units where their technical skills can be leveraged. One could, for instance, imagine that train-ing in the use of drones became a standard feature of technically oriented educational programs at the high school and university level.

7.3 Producers' capacity to absorb use-related knowledge

In order to fully benefit from more innovation-capable users, producers could also emphasize building up their capacity to absorb use-related knowledge. While the antecedents of firms' ability to absorb knowledge from their environment is well-understood, having been the subject of extensive research into the dynamics of absorptive capacity (Cohen & Levinthal, 1990), we only have relatively little knowledge about what it takes to effectively absorb information specifically about user needs and user innovations (see e.g. Schweisfurth & Raasch (2018) for an exposition). However, the Ukrainian case does provide indications of how such practices might be developed: embedding users within producer firms might be one pathway (Schweisfurth & Raasch,

2015), but so may embedding technical workers within frontline units, participating in innovation-oriented user forums, and undertaking training of users at various levels. To function well, of course, such practices are dependent on military organizations allowing for such inter-actions.

7.4 Military procurement and industrial policy

Our observations also carry implications for military procurement and industrial policy. Here, we would suggest thinking about military procurement as more than the acquisition of weapons and equipment, and about producers of military drone technology as more than simply providing today's technology. Military procurement could be understood as a way to finance the build-up of an industrial capacity around drone innovation and manufacturing, not just as a way to acquire drones for military use (see e.g. Mazzucato (2013) on industrial policy and the 'entrepreneurial state'). Industrial policy might also seek to directly support the growth of a drone industry through channels like subsidies, research financing, loans, support of cluster creation, encouragement of university-industry partnerships, etc. Here, we would underscore that one lesson from the Ukrainian case is that what is important here is not just the capacity to produce drones at great scale and to innovate quickly. It is the capacity to innovate quickly in response to user needs, with users, and in ways that enable users to innovate 'on top of' producer innovation. It seems that supporting such absorption-capable producers through both procurement practice and industrial policy is particularly relevant.

7.5 Different countries will have to learn different lessons from the Ukrainian experience

It bears mentioning that these policy recommendations do not take full account of the institutional context in which they would have to be implemented, and arguably cannot do so without considerable further analysis. Without such further work, it is not possible to fully target these recommendations to, for instance, a Swedish defence industry and industrial policy context that is likely to be evolving rapidly in response both the Sweden's recent NATO membership and evolving markets for defence industry products. We would, however, strongly encourage such further work to ensure that policy steps are calibrated with national contexts, capabilities and constraints. It seems pertinent to consider for instance industrial structure, current defence industry capabilities, human capital endowments and education systems, current and past conscription practices, military capabilities and organization, current and past industrial policy practices, the urgency of military and security threats, and the political will to bear different kinds of costs. Given such differences, different countries will have to learn different lessons from the Ukrainian experience, and lessons learned will have to be adapted to local contexts in order to add value (e.g. Ansari et al, 2010).

7.6 Beyond military R&D into R&D in civilian sectors

A large body of literature has convincingly documented that user innovation occurs widely across the economy. While the earliest documentary evidence came from niche fields (e.g. von Hippel, 1976), subsequent scholarship documented that up to a third of users in fields like open-source software, surgical equipment, and extreme sports developed innovations for their own use (von Hippel, 2005). Representative surveys of

firms found that up to forty percent of them developed process innovations for in-house use (i.e. as users), while representative surveys of consumers found that up to six percent of all consumers develop innovations for their own use (de Jong, 2016).

A case study, such as this study, is an in-depth analysis of a particular setting in time and place. However, the actual phenomena of user and producer interaction are similar, and we would therefore suggest a set of policy related insights from the literature for the civilian sector which is in alignment with what found in this case study.

- Supply of human capital with technological skills. Engineers are overrepresented among user innovators (Bengtsson & Edquist, 2022), and Bloom et al. (2019) provide evidence that a higher share of STEM-educated individuals contributes to greater innovation in the economy. The Ukrainian case supports this pattern, showing that technical skill training has dual-use effects—stimulating innovation in both civilian and military sectors. Policies that promote early technical training, for example integrating technology education in elementary schools, can therefore expand the supply of technically skilled users.
- Access to technological infrastructure. Evidence from Ukraine and other contexts suggests that user access to technological tools in the civilian sector can enhance innovation (Svensson & Hartmann, 2018). Policymakers can strengthen this effect by supporting technology infrastructure—such as subsidizing broadband expansion (Åkerman, 2015) or establishing maker spaces in public institutions like hospitals (Svensson & Hartmann, 2018).

8. Conclusion

Since Russia's 2022 invasion of Ukraine, we have witnessed an astounding rate of innovation in military drone use. Our findings suggest that, on the Ukrainian side of the conflict, user in-novation is central to understanding both the high rate of innovation, and the particular form that innovation has taken. It is very difficult to imagine that the kind of innovation that we observe in the conflict would be possible without extensive user contributions, and it is arguably in no small part because of user innovation that this has become the first 'Drone War'. Howev-er, we also need to take account of both the non-typicality of Ukrainian forces as regards their preparedness to engage in innovation and the unique ways that user innovation is organized for within them, as well as the features of the producer firms that allow them to complement users as extensively as seems to be the case. The war is an empirical confirmation of user innovation theory, but also an illustration of the complements that allow user innovation to occur, and be impactful, at this kind of scale.

This conclusion is bound by the limitations of the methods that we apply, as is invariably the case. We have relied on secondary sources which obviously create both problems and opportunities. The opportunity provided by these sources is that they give us insight on innovation dynamics across a wide front, in a context that is notoriously hard to study, and where good data is hard to come by. Alas, they also suffer from a range of biases and shortcomings. Most palpably, we often find ourselves lacking in-depth descriptions of theoretically important dynamics that are hinted at in the data, as well as an absence of data on dynamics that one would expect to play out, but that simply might not get reported, either because they are not considered interesting by reporters and their lay readers or because they are in some way counter-normative. Even as drones have all but eliminated the Clausewitzian fog of war on the battlefield, that fog still refracts and obscures the images that we get of the innovation processes that bring them into being.

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