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Future Challenges for Israel's Iron Dome Rocket Defenses

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Executive Summary

After Hezbollah fired thousands of rockets at northern Israel during the 2006 Israel-Hezbollah War, the Israeli government began a crash program to find a technological solution to the rocket threat. The result was Iron Dome, which shot down its first rocket on April 7, 2011, and saw large-scale combat during wars in 2012 and 2014. The system has been hailed in Israel and worldwide as a success, with the Israeli military claiming a 90 percent interception rate. Some American defense commentators have even touted Iron Dome as evidence in favor of ballistic missile defense. However, serious questions remain about Iron Dome's true technical efficacy, both in terms of its past performance and how it is likely to perform in the future under different conditions. Because so much about Iron Dome is classified, information provided by the Israeli military cannot be independently verified. Analyses performed by outside experts—both those questioning Iron Dome's efficacy and those defending the Israeli government's claims—are inconclusive.

Assuming for the sake of argument that Iron Dome did, in fact, perform as advertised during its previous engagements, it is far from certain that it will be as successful in future engagements, where the volume of rocket fire will be higher and the rockets more accurate. This paper argues that Israel may have already reached "peak Iron Dome," and the system's military and political benefits will decrease in future wars until another technological breakthrough is made on rocket defense. This is not to say that Iron Dome was not worth the cost and should not have been procured. But expectations about Iron Dome from the Israeli military, Israeli civilians, and interested parties abroad should be tempered. If they are not, Iron Dome's decreased success rate in future wars may pose political problems for Israel domestically and give Israel's adversaries a decisive propaganda victory.

Introduction

Ask any Israeli to name their country's most important military innovation over the last decade and you are sure to hear the same answer over and over again: Iron Dome. In the eyes of many Israelis, Iron Dome is a uniquely Israeli accomplishment. After discovering how serious the rocket threat to Israel's security was, the Israeli defense industry quickly developed a breakthrough weapon that captivated the world and has kept Israel largely safe from rocket attacks ever since.

There is truth to this version of events, but as with all stories of national pride, the complete story is more complicated. Iron Dome has no doubt played an important role in Israel's recent military conflicts with Hamas in the Gaza Strip, but its success against Hamas's rockets is not without controversy, and its success in future wars is far from certain. This paper has three main goals: to provide an overview of Israel's threat environment and the history that led to Iron Dome's creation; to examine the debate about Iron Dome's technical efficacy; and to speculate on Iron Dome's future challenges and its role in Israeli defense policy.

The paper will begin with a history of the missile and rocket threats that have faced the Middle East in general, and Israel in particular, over the past several decades. This context is important for understanding the decisions Israel has made with regard to rocket defense. Next, it will detail the defining event that forced Israel to crash-develop a rocket defense system, the 2006 Israel-Hezbollah War, and Iron Dome's rapid development. It will then examine Iron Dome's performance in Israel's two most recent conflicts with Hamas and explain why its performance has caused such controversy. The paper will end with an assessment of the problems Iron Dome is likely to face in future wars, regardless of Iron Dome's true performance in past wars, and will propose that Israel has likely already hit "peak Iron Dome," the height of the system's ability to protect Israel and provide the Israeli government with political and military maneuvering room.

Israel's Security Environment, the 2006 Israel-Hezbollah War, and the Rationale for Iron Dome

Israel's Security Environment and the Missile Threat in Context

Since its creation as a state in 1948, Israel has been at war with its Arab neighbors. This war has taken many shapes, from large-scale conventional wars to guerilla raids to terrorist attacks. The threat posed by ballistic missiles and rockets did not enter the minds of Israel's military planners until decades after the state was founded given the multitude of other, more pressing threats. As a small state without the resources, population, or economic strength to fight long wars or wars of attrition, Israeli military doctrine has always rested on three main pillars: deterrence, early warning, and rapid battlefield decision.¹

By developing an extremely well-trained and competent reservist-based fighting force, Israel hopes to dissuade its enemies from initiating large-scale war in the first place. By retaliating swiftly and strongly to even small provocations, the Israel Defense Forces (IDF) make wars of attrition, which it cannot win, too costly for its enemies to consider. If a large-scale war that threatened Israel's existence were to take place, Israel relies on its intelligence services to

provide enough warning time for the reserves to be called up—Israel’s standing army is far too small to fight a major war without the reserves that comprise the majority of the IDF. Once such a war begins, Israel must bring about an end to the war on favorable terms as quickly as possible. This had led to an ethos of offensive maneuver meant to move the battle to enemy territory and achieve battlefield decision as quickly as possible.² For most of the country’s history, defense was noticeably absent from the nation’s defense doctrine. A small country like Israel simply did not have the means to invest in defensive assets which in any case would have led to a strategy that placed Israel at a structural disadvantage vis-à-vis its adversaries.

The first use of ballistic missiles in the region was during the 1973 Arab-Israeli War, when Egypt fired three Scud missiles at Israeli military positions just before a ceasefire went into effect.³ During this war, Syria also fired several Frog-7 heavy artillery rockets into northern Israel. In accordance with its defense doctrine, Israel responded to the Frog-7 attacks by sending its air force to retaliate against high-value targets in Syria. The retaliation was successful and intra-war deterrence was achieved; Syria did not fire Frog-7 rockets at Israel again.⁴ This validated Israel’s belief that no defense against such missiles and rockets was needed beyond a strong retaliatory capability.

The use of ballistic missiles during the Iran-Iraq War, which lasted from 1980 to 1988, was much more consequential. Both Iraq and Iran fired ballistic missiles at each other’s cities, sowing fear and causing panic, especially on the Iranian side.⁵ Towards the end of the war in 1988, in the finale of the “war of the cities,” Iraq fired close to 200 ballistic missiles at Iran, killing some 2,000 people.⁶ These devastating strikes contributed to Iran’s decision to accept a ceasefire, demonstrating the political utility of ballistic missiles when employed against civilian targets.

It was during this time that Israel began reconsidering its purely offense-based retaliatory strategy for deterring the use of ballistic missiles, though not just because ballistic missiles began entering the arsenals of Arab armies in larger numbers or because their utility as both a military and political weapon was demonstrated during the Iran-Iraq War. U.S. President Ronald Reagan, in office for much of the 1980s, was a staunch advocate of ballistic missile defense (BMD), and some in Israel saw Reagan’s Strategic Defense Initiative (SDI), dubbed “Star Wars” by its critics, as an opportunity to deepen cooperation with the United States.⁷ The decision to cooperate with the United States on SDI was controversial in Israel because of the program’s defensive nature. Why should Israel spend its limited resources on a project of dubious value when deterrence through the threat of retaliation would suffice? But because of the opportunity to deepen cooperation with the United States, and because of the growing ballistic missile threat,⁸ Israel signed on to SDI and began its journey to becoming a world leader in missile defense.

The experience of the Persian Gulf War in 1991 strengthened the position of missile defense advocates in Israel. In an effort to goad Israel into attacking Iraq and thus splinter the U.S.-led coalition formed to kick Saddam Hussein out of Kuwait, Iraq fired 31 Scud missiles at Israeli cities. In order to convince Israel not to retaliate, the United States deployed Patriot PAC-2 missile defense batteries to Israel and committed the U.S. Air Force to destroying the Scud launchers. These measures were unsuccessful. The Patriot batteries were shown to be almost completely ineffective at stopping the incoming Scuds, and the Scud launchers were too difficult

for the U.S. Air Force to find and destroy.⁹ After the Persian Gulf War, Israel became fully committed to BMD and developed its Arrow missile defense system, designed to intercept ballistic missiles during the midcourse phase of their flight.

While Israel was focusing on the threat posed by ballistic missiles in the hands of enemies such as Saddam Hussein and the Iranian Ayatollahs, another related threat to Israel's security was forming along its borders that received scant attention. In an effort to push the Palestine Liberation Organization away from Israel's border with Lebanon, Israel launched a massive incursion into Lebanon called Operation Peace for Galilee in 1982. After the invasion, the IDF maintained an occupation of southern Lebanon as a security zone until the year 2000.¹⁰ In response, a Shia militia called Hezbollah arose (with Iran's help) to force the Israelis out of the security zone.

Hezbollah used classic guerilla and terrorist tactics against the Israeli presence in southern Lebanon, with varying degrees of success, but it realized that if it was to have any strategic success against Israel, it would need a way to deter Israel's military superiority, or bypass it to put pressure on the Israeli public directly. Perhaps drawing lessons from Saddam Hussein's success with ballistic missiles against Iran during the Iran-Iraq War and against Israel during the Persian Gulf War, Hezbollah found its deterrent in the form of short-range rockets. Calculating that Israel had no defense against these weapons and that Israel's superior offense capabilities would be unable to target all of Hezbollah's launchers with stand-off weapons (just as the United States was unable to hunt down Saddam Hussein's Scud launchers in 1991), Hezbollah prepared for a war of attrition that would utilize these rockets in a strategic, not just a tactical, manner.

Most of Hezbollah's rockets are of the Katyusha family—various types and models of the Soviet World War II-era artillery rockets that are cheap and ubiquitous to this day.¹¹ Though they are inaccurate and have a range of only 20-25 km, when fired as a “statistical weapon,” that is, in large volleys, a certain percentage of the rockets will hit valuable targets, and the others will sow fear and panic. Katyushas, mortars, and other artillery had been fired into Israel from Lebanon before, mostly by Palestinian militants, but they had never been used strategically until Hezbollah began developing a strategy to use them in this way in 1992. After Israel assassinated Hezbollah leader Abbas Musawi in early 1992, Hezbollah's new leader, Hassan Nasrallah, fired Katyushas into northern Israel in retaliation, marking the first use of these weapons by Hezbollah.¹² No longer would Israel have free reign in Lebanon—Hezbollah now had the capability to influence Israeli policy inside the security zone by being able to strike outside of it. This marked the beginning of a new dynamic that would become increasingly apparent over the next decade.

In 1993, in response to an increase in Hezbollah attacks against Israeli forces in the security zone, Israel launched Operation Accountability. Hezbollah had prepared its fighters for face-to-face combat with the Israelis; instead, Israel used its overwhelming conventional and technological superiority to launch stand-off attacks that devastated Hezbollah positions without the need for close quarter fighting.¹³ This drove Hezbollah to rely further on its Katyusha strategy, which reduced the utility of Israel's conventional superiority and played to Hezbollah's greater willingness to engage in attrition-based warfare.

The next major round of fighting came in 1996. After Hezbollah launched a barrage of rockets into northern Israel, wounding 38 people, Israel responded with Operation Grapes of Wrath. Israel stuck to employing the stand-off strategy that it had used three years earlier; Hezbollah, however, did not wait to confront Israeli soldiers face-to-face but instead fired hundreds of Katyusha rockets at Israel, disrupting life for thousands of Israelis.¹⁴ Hezbollah was able to continue the rocket fire throughout the fighting and the IDF was unable to stop it.¹⁵ After Operation Grapes of Wrath, Hezbollah drew the correct conclusions and realized the power of large quantities of these low-quality weapons that could terrorize the Israeli homeland—a capability against which the IDF’s conventional superiority was powerless. Israel also realized its inability to address this threat, and began a development project with the United States to find a solution. That solution was the Nautilus, or the Tactical High Energy Laser (THEL).

Just like BMD before it, THEL was controversial in Israel. Many experts criticized its cost and its performance.¹⁶ It was a bulky system, taking up the size of six city buses, and was prone to leaking the chemicals used to create the laser interceptor.¹⁷ Such a system would be a sitting duck prone to counter-fire, and dozens of systems would be needed to defend northern Israel, which would be prohibitively expensive.¹⁸ After successful trials in New Mexico, the system was scrapped in 2005 and judged unsuitable for actual battlefield conditions.¹⁹ Instead of quickly coming up with an alternative to THEL—either another defensive system or an alternative war doctrine to deal with the rocket threat posed by Hezbollah—Israel went back to ignoring the problem and reverted to the same stand-off strategy that had failed it in Operation Grapes of Wrath. That decision would quickly come back to haunt Israel.

Wake Up Call: The 2006 Israel-Hezbollah War and the Need for Rocket Defense

Israel withdrew its forces from southern Lebanon in 2000 with a promise to the Israeli public to respond to any Hezbollah attacks from the border. For a myriad of political and operational reasons, those responses never materialized. Of greater importance than the occasional provocation was Hezbollah’s impressive preparation for war with Israel, one that would double down on the rocket strategy that served it so well in the past. Hezbollah established rocket-firing units along the border in villages and in open areas supported by vast tunnel networks for transporting weapons and manning defensive positions.²⁰

By 2006, Hezbollah had amassed a stockpile of 12,000 to 13,000 rockets and missiles supplied mostly by Iran and Syria, most of them 122mm Katyushas.²¹ Other rockets and missiles included 220mm and 302mm rockets, as well as Fajr-3 and Fajr-5 rockets supplied by Iran.²² Knowing that Israel’s stand-off firepower would not be able to destroy all of these rockets or their launchers in a politically acceptable amount of time, Hezbollah prepared to be able to fire rockets into Israel for the duration of any conflict. With such a large arsenal of rockets, even if many were destroyed by Israeli airpower before they could be used, enough would survive for a long campaign of attrition—exactly the type of conflict the Israelis were unwilling and unable to fight.

On July 12, 2006, Hezbollah launched an operation along the border with Israel that saw two Israeli soldiers kidnapped and eight killed. Israel’s new and inexperienced leadership saw an opportunity to severely weaken Hezbollah and score popularity with the Israeli public for avenging Hezbollah’s hostility and bringing the two captive soldiers home. However, the IDF

was unprepared for a confrontation with Hezbollah and was even more unprepared to deal with the use of rockets in a strategic manner. The war dragged on for 34 days and saw 4,228 rockets fired into Israel, the largest sustained shelling of a geographical area since the Iran-Iraq War.²³ On average, 100 rockets were fired per day, though towards the end of the war it became closer to 200, demonstrating Hezbollah's ability to control the tempo of its operations even under massive aerial assault.

Roughly one-fourth of the rockets fired landed in populated areas, while the rest landed in open spaces and caused no damage other than fires. In addition to disrupting normal life for hundreds of thousands of people in northern Israel, 53 Israelis were killed, over 2,000 were wounded, and there was extensive damage to homes and infrastructure.²⁴ The IDF's inability to stop the rockets, along with the IDF's other strategic and tactical failures during the war, enabled Hezbollah to claim victory as the first Arab fighting force able to fight Israel to a draw on the battlefield.²⁵

Because of Israel's small size and because of the massive quantity of Katyusha rockets fired, these tactical weapons were used to strategic effect by Hezbollah. It became clear that the IDF's conventional superiority would not be able to effectively hunt down and destroy all of the Katyusha launchers or the stockpiles of rockets themselves, and in future wars Israel would be vulnerable to the same threat of massive shelling. The Israeli public saw the war and the unrelenting rocket fire from Lebanon as a massive failure. It was clear that a solution needed to be found to protect Israeli civilians from rocket fire, both during times of relative calm and during times of intense fighting. In the debate about the role of defense in Israel's military strategy, those promoting defense—with missile and rocket defense front-and-center—had finally won.

Iron Dome's Development and Specs

The Israeli Ministry of Defense (IMOD) awarded Israeli defense contractor Rafael the contract to develop a rocket defense system in February 2007.²⁶ Rafael, however, would not have to start from scratch. Despite the United States and Israel abandoning THEL in 2005 and the IDF focusing on its stand-off firepower strategy, the head of the IMOD's R&D division, Danny Gold, was looking into anti-rocket technology without the approval of his bosses starting in 2005.²⁷

Believing Israel had the technical know-how and ingenuity to address the rocket threat, Gold began work on what would become Iron Dome before the 2006 Israel-Hezbollah War even started. After Rafael was awarded the contract, the IMOD and Rafael engineers worked around the clock, even receiving a special exception from Israel's Rabbinate to work on the Sabbath.²⁸ Full-scale development began at the end of 2007, just months after the contract was awarded.²⁹ After three and a half years of development, Iron Dome became operational, and on April 7, 2011, it shot down its first rocket, a Grad artillery rocket fired from the Gaza Strip by Hamas.³⁰

Information about Iron Dome's specifications is difficult to confirm, but Jane's Information Group has some data publically available. These technical specifications are only estimates, and other publications have produced estimates that slightly differ. According to Jane's, Iron Dome

is an all-weather counter rocket, artillery, and mortar (C-RAM) system capable of detecting and intercepting incoming projectiles within ranges of 4km to 70km.³¹ Each battery of the system is comprised of three components: a radar for detecting and tracking incoming threats; a battle management and fire-control center; and three missile launching units, each carrying 20 Tamir interceptors.³²

Iron Dome's radar, an EL/M-2084 S-band radar, is an Active Electronically Scanned Array multirole radar that locates the launch origin of incoming rockets and mortars, tracks the projectiles in flight, calculates an intercept solution, and directs the interceptor to the interception point.³³ The target acquisition process is reportedly performed in anywhere from less than one second to seven seconds, with the interceptor launch taking place just one second after that.³⁴ It can locate the source of artillery and rocket fire with a circular error probable (CEP) of 490ft (150m) at 31mi (50km), according to *Military Periscope*, an online weapons database.³⁵ Each battery is estimated to be able to protect a 58mi²/150km² area.³⁶

Using the information gathered by the radar, soldiers at the battle management and fire-control center determine if the rocket is on a trajectory to hit a populated area (or areas of strategic importance such as industrial sites or military bases that the state would want to defend). If the rocket is on target to land in an open field or the desert, no further action is taken—the rocket is ignored and left to explode in the open where it will not cause any damage. If the rocket is on target to land in a populated or important area, the battle management and fire-control center will take appropriate action. The details on how automated this process is, and exactly how decisions to intercept are made, are not publically available, but it does appear that the system has a “man in the loop” who performs some level of decision making about whether to intercept an incoming rocket or not.³⁷ According to one report in *Aviation Week*, Iron Dome is capable of operating fully automatically, but the Israeli Air Force chooses to have soldiers confirm each intercept.³⁸

If the decision is made to intercept, a Tamir interceptor is fired from one of the launching units and sent up into the sky to meet the incoming threat. According to Jane's, the Tamir interceptor is a 90kg solid-fuel missile with a length of 3m and a diameter of 160mm. It has a minimum range of 2km and a maximum range of 40km³⁹ with a top speed of Mach 2.2 (700m/sec).⁴⁰ Specifics about the warhead are unavailable, but it is reported to be a proximity fuse fragmentation warhead that communicates with the radar to receive guidance information via uplink communication.⁴¹

After being guided to the general location of the intercept point, the Tamir's on-board radar seeker takes over and maneuvers closer to the target. Once it is close enough, it detonates and sprays rods into the target warhead (attempting to do so at the highest possible altitude to reduce the concentration of any chemical or biological agents that the incoming missile might be carrying). The Israeli government has never confirmed how many Tamir interceptors it fires at each incoming rocket. Reports indicate that early on, Iron Dome would fire two interceptors for each incoming rocket on track to hit a defended area, but as the system has improved and received upgrades, it now fires only one. An exception to this policy may exist for rockets fired at Tel Aviv, where, according to videos capturing the interceptions, two rockets are fired to increase the probability of a successful intercept.⁴²

The discrimination process—assessing which rockets pose a threat and ignoring the ones that do not—is essential both for cost control and the viability of the rocket defense concept. Iron Dome batteries and Tamir interceptors are not cheap, especially when compared to the cost of the rockets and mortars they are engaging. Exact figures are not available, but best estimates put the cost of each Iron Dome battery at about \$50 million, including the radar and the battle management center. Estimates for the cost of a single Tamir interceptor range from \$20,000 to \$100,000,⁴³ with most estimates claiming around \$50,000. Meanwhile, Qassam and Katyusha rockets range from hundreds of dollars to the single thousands of dollars. Such a cost-exchange ratio would be prohibitively expensive if Iron Dome were required to expend \$50,000 each time a \$500 rocket were fired at Israel.

Given the volume of rocket fire targeting Israel, the IDF would run out of interceptors if it had to engage all incoming rockets as opposed to the smaller percentage of rockets whose trajectories indicate they will land in the protected envelope. Providing coverage for the entire country is also a costly endeavor. According to most estimates, Israel has nine Iron Dome batteries, and Israeli officials estimate it would take 13 batteries to cover the entire country, which they plan to do.⁴⁴ While Israel developed Iron Dome on its own, the United States provided Israel with monetary assistance to the tune of around \$1 billion between FY2011-FY2016 for production and procurement, greatly offsetting the cost that Israel's much smaller defense budget would have to allocate.⁴⁵

It is unclear what Israeli officials mean when they talk of providing coverage to the entirety of Israel's territory. Do they mean providing radar coverage and the ability to intercept a rocket anywhere in the country, or do they mean the ability to intercept a high volume of rocket fire on multiple parts of the country simultaneously? The answer to this question, among others, will have serious policy consequences for Israel, and will be discussed later in the paper.

Iron Dome's Performance: Competing Claims about Technical Efficacy

After Iron Dome's debut on April 7, 2011, it was put to the test in two major military conflicts between Israel and Hamas in the Gaza Strip. Israel's Operation Pillar of Defense, a week-long mini-war between Israel and Hamas, took place from November 14 to November 21 in 2012. Another much longer and bloodier war followed two years later, called Operation Protective Edge by Israel. From July 8 to August 26, 2014, Hamas and other Islamist groups in Gaza launched thousands of rockets into Israel while the IDF conducted thousands of airstrikes in Gaza along with limited ground incursions. Iron Dome was the darling of both operations, both in Israel and around the world. Commentators touted the success of the system, often using phrases like "game changer" and "stunningly effective." In Israel, Iron Dome became something of a cultural icon, inspiring songs, skits, and even tattoos.⁴⁶ But in the midst of the outcry of support and pride for Iron Dome, a few skeptics emerged. Their analyses have cast doubt over the conventional wisdom about Iron Dome and led to a debate among experts as to whether Iron Dome's performance is actually what the Israeli government claims.

This section of the paper will look at the competing claims about Iron Dome's technical efficacy in both conflicts and attempt to assess the validity of each side's argument as best as possible

with the limited information available. Two realities make such an analysis difficult: the fact that most of the data about Iron Dome is provided by the Israeli government and cannot be independently verified, and the fact that a great deal of information about Iron Dome remains classified. Given these constraints, the conclusions derived from this examination will not be definitive. The concluding section of the paper that assesses the proper role of rocket defense in Israel's defense strategy will take into account the wide array of possibilities about Iron Dome's true technical capabilities.

Operation Pillar of Defense: November 14 – 21, 2012

Over the eight days of this mini-war, Hamas and other Islamist groups in Gaza fired “more than 1,506 rockets” into Israel, according to the IDF.⁴⁷ Other estimates vary, and Hamas claims a slightly higher number, but all estimates hover around 1,500. The IDF claims that it intercepted 421 rockets successfully, achieving an 84 percent interception success rate.⁴⁸ Working backwards, this means that of the 1,506 rockets fired into Israel, 501 rockets were on track to strike populated areas ($421 / .84 \approx 501$). According to some sources, the IDF claims that the number of rockets that would have hit defended areas was 480,⁴⁹ which is slightly different from the 501 number derived from using the 421 and 84 percent numbers also taken from the IDF. This discrepancy is not explained anywhere in the open literature.

Assuming the 421 and 501 estimates are correct, that means that there were 80 rockets that Iron Dome attempted to intercept but failed to do so, meaning these 80 rockets must have landed within areas defended by Iron Dome. Some reports cite the IDF as claiming that the number of failed interceptions was 58, which is a difference of 22 rockets from the 80 estimate.⁵⁰ A police report from the southern district of the Israel Police says that 109 rockets fell in built-up areas, which is somewhat close to the 80 rocket estimate but almost double the 58 rocket estimate claimed by the IDF.⁵¹

Needless to say, the lack of definitive data about the number of rockets fired, the number of rockets on track to hit defended areas, the number of rockets Iron Dome attempted to intercept, and the number of rockets Iron Dome successfully intercepted introduces skepticism about the IDF's claims. It may be that the IDF has this data but is not releasing it or allowing others to independently verify it; it might also be that during the chaos of war the data collection process was imperfect and exact numbers simply aren't available. Over the course of the war, five Israeli civilians and one soldier were killed by rocket fire.⁵² Operating the system during the war cost between \$25 million and \$30 million, including the cost of the expended Tamirs.⁵³

Operation Protective Edge: July 8 – August 26, 2014

The data for Operation Protective Edge has even more variance than the data for Pillar of Defense. According to an Israeli defense expert who received an oral briefing by an IDF spokesman (and asked to remain anonymous in this paper), 4,591 rockets and mortars were fired at Israel during the 50-day war.⁵⁴ One hundred and ninety-seven of those exploded or landed in Gaza, leaving 4,394 that actually landed in Israel. Of those, 3,434 landed in “open spaces,” areas not in Iron Dome's envelope. That means that 960 rockets were judged by Iron Dome to pose a threat to defended areas.

Of these 960 threatening rockets, Iron Dome successfully intercepted 735, leaving 225 that hit within the protective envelope. Of those 225, Iron Dome engaged 70 but the engagements were unsuccessful, according to a report from *Aviation Week*.⁵⁵ No explanation is given for why Iron Dome did not attempt to intercept the remaining 155 rockets that hit within the defended envelope, though it may be possible that some of these were actually mortars with ranges of under 4km, which Iron Dome is not designed to defend against. Other estimates for the total number of rockets fired vary slightly, while other estimates for the number of rockets that landed in open areas vary by a few hundred. The main explanation for this wide variance is that some estimates include mortar attacks while others only include rocket attacks.⁵⁶ Discrepancies could conceivably also occur from accounting that relies on daily reporting by Israeli news outlets during the war, which may report inaccurate or incomplete information under stressful wartime conditions.

The percentage success rate during this war touted by the IDF and reported by the media worldwide is 90 percent, presumably derived from the 735 successful intercepts plus the 70 unsuccessful intercepts ($735 + 70 = 805$; $735 / 805 = .913 \approx 90$ percent). However, if one takes into account that 225 rockets reportedly landed within the protective envelope, a more honest percentage success rate would be 76 percent ($735 / 960 = .7656 \approx 76$ percent), the number of interceptions divided by the number of rockets that actually hit built-up areas, regardless of whether Iron Dome attempted to intercept them or not. Over the course of the 50-day war, rockets killed two people, one civilian and one soldier.⁵⁷

The IDF's claims about Iron Dome's performance are impressive (see Table 1 on page 10 for a summary of these claims). Over the course of these wars, the Israeli population and the Israeli government both developed expectations about what Iron Dome is supposed to provide. While Iron Dome was still in the developmental stage, it was not clear what the exact objective of the system would be—was it to save as many Israeli lives as possible, provide protection to IDF bases, or provide decision makers with more options? After being seen as such a success in Israel, the expectations for Iron Dome can be summarized as follows. The Israeli public expects Iron Dome to protect as many lives as possible and limit damage to property.⁵⁸ All population centers in Israel now expect to be covered if they are within rocket range. Israelis see Iron Dome as part of the state's moral obligation to do everything within its power to protect its citizens.

The Israeli government sees Iron Dome as an instrument of political and military flexibility. Because Iron Dome gives the Israeli population a sense of security and shows the public that the government is “doing something” to protect them, there is less public pressure on the government for military action. This gives the Israeli government more political maneuvering room and enables decisions about the use of force to be made with less political considerations.⁵⁹ According to many Israeli officials and commentators, if it weren't for Iron Dome, Israel would have been forced to invade Gaza to stop the rockets or the government would have paid a political price. Since the cost of a single day of IDF ground operations in Gaza is estimated to cost around \$260 million,⁶⁰ and the cost in Palestinian civilian lives and the lives of Israeli soldiers would be catastrophic, anything that gives the Israeli government more options short of invading Gaza is beneficial.

These expectations have produced tangible benefits for Israel while also setting the stage for potential drawbacks in the future (to be addressed in later in the paper). In addition to saving lives and providing decision makers with greater flexibility, Iron Dome was a massive propaganda victory for Israel and helped Israelis view the 2012 and 2014 wars as successes even though Hamas was not defeated and the rocket fire continued throughout both operations. Israeli researchers even found that confidence in Iron Dome helped reduce Post-Traumatic Stress Disorder among those affected by Operation Protective Edge.⁶¹

	Pillar of Defense	Protective Edge
Rockets/Mortars Fired	1,506	4,591
Rockets Intercepted	421	735
% Success Rate	84%	90%
Deaths	6	2
Injuries	240	N/A
Cost	\$30 million	N/A

Table 1: IDF Claims about Iron Dome’s Success Rate in 2012 and 2014⁶²

The benefits that are derived from the IDF’s claims about Iron Dome are real, but they do not change the fact that the information provided about the system’s actual performance has not been verified by independent parties. There is still much important information that the IDF has not produced, which deprives these figures of the context necessary to fully assess Iron Dome’s performance. Helpful additional information would include: how many interceptors were fired at each incoming threatening rocket; when were batteries undergoing reloading or maintenance, and does this account for some of the threatening rockets that Iron Dome did not engage; were there technological glitches or instances of human error; and where did each rocket land?⁶³ Having answers to these questions would help provide a more complete picture and make an assessment of Iron Dome’s technical efficacy much easier to perform. In the absence of such information, the IDF’s claims must be met with a healthy degree of skepticism.

Iron Dome a Hoax?

That skepticism did not take long to materialize. Just months after Operation Pillar of Defense, Theodore Postol, a missile expert and professor of Science, Technology, and National Security Policy at the Massachusetts Institute of Technology, wrote that Iron Dome could not have performed as well as the Israeli government claimed. Postol’s analysis immediately gained attention among academics in the United States due to his past success in exposing the failure of the Patriot PAC-2 batteries during the Persian Gulf War. A handful of other skeptics also emerged, but since Postol’s analysis is the most well-known and comprehensive, this paper will focus on evaluating his claims.

Postol analyzed footage of Iron Dome interceptions, mostly videos uploaded to the internet by Israelis who captured the event on their cellphones, and concluded that Iron Dome’s Tamir interceptors were not engaging the target rockets in a way that would lead to a high success rate.⁶⁴ In fact, Postol estimates that Iron Dome’s true interception rate is closer to 5 percent. In

order to understand how Postol came to this conclusion, it is important to understand the basic physics of rocket defense.

The objective of rocket defense is to explode or otherwise disable the warhead of the incoming projectile. This must be done either by slamming an interceptor's kill vehicle into the warhead of the incoming projectile (known as a hit-to-kill interception, likened to "hitting a bullet with a bullet"), or by exploding an interceptor's warhead near the incoming projectile and spraying it with shrapnel that explodes or disables it (known as a fragmentation or explosive detonation interception). For fragmentation interceptions, which is the method Iron Dome reportedly uses, engagements between the interceptor and the incoming rocket need to be head-on, or antiparallel.⁶⁵ If the interceptor approaches the target projectile from the side or from behind, it will explode and spray its shrapnel into the rocket motor, not the warhead at the tip of the descending rocket. During the descent phase of a ballistic projectile, the rocket motor will have already expended its fuel, meaning it is essentially an empty tube.⁶⁶ Because the descending front-end of the rocket is the heavy end, blowing holes in the empty motor tube most likely will not cause the rocket to tumble or otherwise alter its stable trajectory. The only way to explode the interceptor warhead in a way that will send shrapnel into the target warhead is by approaching the target warhead head-on (see section A of Figure 1).

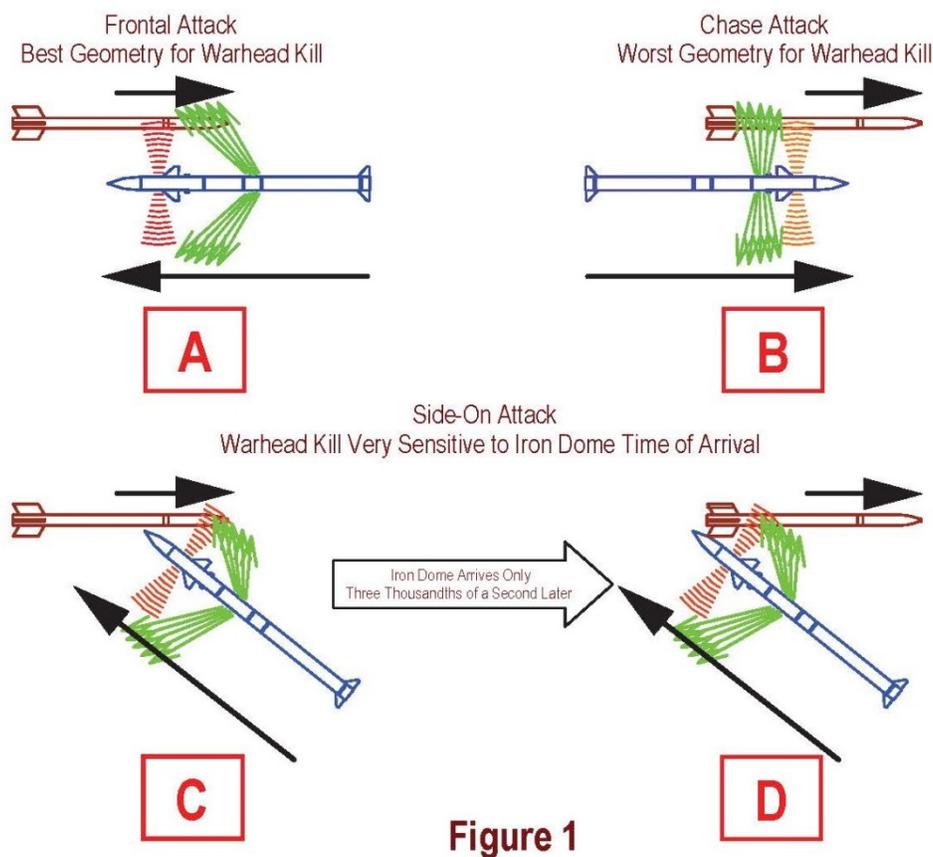


Figure 1: Possible Interceptor Confrontation Angles⁶⁷

This confrontation angle allows the Tamir's radar seeker to detect the incoming projectile, estimate where the front of the projectile is, and calculate how long it will take the front of the projectile to line up with the Tamir's warhead (located behind the radar seeker).⁶⁸ Approaching the target projectile from behind will cause the radar seeker to think the end of the target projectile is in fact the front of it (see section B of Figure 1). Side engagements are also extremely unlikely to line up such that the shrapnel from the interceptor hits the warhead of the incoming rocket.

By looking at dozens of Iron Dome interception videos, Postol concluded that fewer than 20 percent of the engagements were antiparallel. He determined this by looking at the contrails of the interceptors as they approached their targets and by looking for asymmetric explosions as a sign that the target warhead had actually detonated. According to his analysis of the footage from both Pillar of Defense and Protective Edge, the Tamirs appear to be maneuvering wildly and chasing the rocket instead of meeting it head-on as it descends on a steep trajectory. Maneuvering at the end of the engagement to chase the rocket indicates the interception is not antiparallel. Richard Lloyd, a former Raytheon employee and consultant for Tesla Laboratories, agrees that the contrails show the Tamirs engaging in maneuvers that indicate interceptions from the side.⁶⁹ Postol also saw no evidence of asymmetrical explosions. If only the interceptor warhead detonates, a spherical explosion would be seen; however, if the interceptor successfully causes the target warhead to detonate, an asymmetric fireball should be seen as both warheads explode next to each other.

The Defenders Respond

Defenders of Iron Dome take issue with the analysis and claims of Postol and the other skeptics. The response to Postol's analysis consists broadly of three arguments. First, Iron Dome's defenders take issue with relying on video footage uploaded to YouTube for a technical analysis of a complex rocket defense system. Hundreds of rocket interceptions occurred, so a random sample of just a few dozen engagements, some of which may be repeat videos of the same engagement shot from different angles, does not meet the threshold of a proper scientific analysis. Uzi Rubin, one of Iron Dome's fiercest defenders and the former head of Israel's missile defense agency, also points out that the videos are often of poor and grainy quality, making it difficult to assess what's happening in the video.⁷⁰ Additionally, Rubin and others say that relying on 2-dimensional footage of a 3-dimensional event without knowing the angle that the footage was shot from makes such videos an unreliable method for evaluating Iron Dome.⁷¹

The second piece of evidence that Iron Dome's defenders point to is the reduction in Israeli casualties from the 2006 Israel-Hezbollah War versus the two wars in Gaza. In 2006, 4,228 rockets were fired into Israel, killing 53 Israelis. This means that it took on average 79 rockets to kill one person. In Pillar of Defense, 1,506 rockets were fired and six Israelis were killed, producing a rocket-to-fatality ratio of 251:1 (Rubin's ratio is different because he counts 1,600 rockets fired and five deaths). With Protective Edge, producing such a ratio becomes more difficult because both rockets and mortars are counted. Rubin assumes roughly 3,000 of the 4,591 projectiles fired were rockets. He also counts only two deaths inside Israel, producing a ratio of 1,500:1. As the number of rockets required to kill a single person increases with each war, and increases substantially from 2006 to 2012, Rubin concludes that Iron Dome must be working as advertised.⁷²

The third argument advanced by Iron Dome’s defenders pertains to damage claims filed by Israelis to receive compensation for destruction caused to their property by aggression from Israel’s enemies.⁷³ This state-run insurance program is funded from tax revenue on property transactions.⁷⁴ Israelis are eligible for compensation even for extremely minor damages, such as scratched paint on a car. A summary of the insurance claims is reproduced from Rubin’s February 2015 paper about Iron Dome in Table 2, with the exact “rockets fired” totals used instead of Rubin’s rounded figures.

War	Rockets Fired	Damage Claims Filed	Ratio Claims/Rockets
2006 Lebanon	4,228	26,653	6.3
2012 Gaza	1,506	3,921	2.6
2014 Gaza	4,591	4,525	0.98

Table 2: Number of Damage Claims and Claims per Rocket⁷⁵

As the ratio of damage claims per rocket fired decreases with each war, Rubin concludes that Iron Dome must be intercepting the incoming rockets effectively. He also cites the actual monetary compensation paid by the Israeli government to citizens who filed claims. According to Rubin’s figures, the dollar amount per rocket was \$29,500 in 2006; \$9,000 per rocket in 2012; and \$5,100 per rocket in 2014.⁷⁶ This decrease in insurance money paid out per rocket is presented as further evidence that fewer missiles were hitting Israel. The still large number of damage claims filed is due to rocket and Tamir interceptor fragments that fall to the ground after a successful intercept and cause light damage to cars and windows.

Assessing the Arguments of Iron Dome’s Detractors and Defenders

Missile defense experts broadly agree with Postol’s assessment that the interceptor must engage the incoming rocket head-on, but the criticism of his method of evaluation is valid. The interceptions that Postol analyzes do not qualify as a random sample of interceptions—there could be a selection bias in terms of which interceptions were captured on film. There is also no way to confirm that multiple videos are not showing the same interception from different angles. The fact that the videos are low-quality and that the distances and viewing angles are unknown also weaken Postol’s case. It is also possible that Iron Dome is meant to perform in a way that Postol and others have not considered. Iron Dome’s design is classified so Postol and others are left to speculate about how the specifics of the system work. Bill Sweetman, an editor and aerospace journalist at *Aviation Week*, posits that it is possible Iron Dome is in fact designed to perform the observed endgame maneuvers and is destroying the warheads of the incoming rockets via some new method.⁷⁷ However, this too is unprovable. Therefore, while Postol raises valid doubts about Iron Dome—and indeed, many of the videos in question do appear to show contrails that indicate wild maneuvers—his analysis is inconclusive.

That being said, the evidence put forward by Iron Dome’s defenders fails to disprove Postol’s arguments, and even raises new suspicions. The arguments about reduced fatalities and property damage are particularly flawed. There are two other variables that can also explain the difference in fatalities and property damage between the 2006 war against Hezbollah and the two wars against Hamas in 2012 and 2014.

The first is the difference in population density between northern and southern Israel. Appendix A shows Israel's population density in the year 2014. As the map makes clear, there are many more localities in northern Israel than there are in southern Israel, and the population density is higher in northern Israel. According to estimates using data from Israel's Central Bureau of Statistics, the combined population of Israel's Northern District and Israel's Haifa District (both targeted by Hezbollah rockets in 2006) was 2,361,700 people in 2015.⁷⁸ Israel's Southern District, which bore the brunt of Hamas's rocket attacks in 2012 and 2014, had an estimated population of 1,217,500 for the year 2015. Thus, Israel's Northern and Haifa Districts have over a million more people than the Southern District, which could help explain the higher casualty rate in 2006. A more detailed analysis of the effect of population density on rocket fatalities and property damage must be performed in order to rule it out as a variable that contributed to the difference in casualty rates between 2006 and 2012/2014.

Another plausible, even likely, explanation for the low fatality figures in Pillar of Defense and Protective Edge is increased civil defense. Israel maintains a system of public shelters and most Israelis have fortified "safe rooms" in their homes that protect against rockets and bombs. Israelis are alerted to seek shelter by a sophisticated constellation of radars and electro-optic sensors that detect launches and trigger air raid sirens in the areas where the rocket might land.⁷⁹ For people close to the Gaza border, that warning time can be as little as 15 seconds.⁸⁰ After the high casualty figures seen in 2006, and the low-frequency but constant rocket fire from Gaza over the past decade, it is a safe assumption that Israelis have become accustomed to quickly seeking shelter when the air raid siren sounds. The IDF is constantly working to improve its ability to give longer warning times, enabling more people to get to safety. There are even a number of smartphone apps, including one from the IDF, that alert people via an alarm on their phone if a rocket is headed their way.⁸¹

Given the low lethality of many of the artillery rockets fired into Israel, such civil defense measures can be extremely effective.⁸² The differences in population density between northern and southern Israel and an increase in civil defense measures are two variables that Iron Dome's defenders do not control for when they assert that Iron Dome must have worked because casualties are lower in the wars that featured Iron Dome and higher in the war that did not. It is also suspicious that Rubín and others do not look at casualties from Israel's Operation Cast Lead, yet another operation in Gaza that lasted for 22 days in December 2008 and January 2009, before Iron Dome became operational. During Cast Lead, 571 rockets and 205 mortars were fired into Israel, killing three people and injuring around 200 others.⁸³ One might expect much higher casualties in the absence of Iron Dome instead of casualty figures that are fairly close to what was seen in the two operations after Iron Dome's deployment. Comparisons between Cast Lead and Pillar of Defense and Protective Edge would remove population density as a variable, but no comparison is made with Cast Lead by Rubín or other Iron Dome defenders.

Differences in population density can also explain the lower numbers of damage claims filed. Additionally, because claims can be filed for large damages as well as small, and for damage caused by debris from a successful interception and damage caused from a successful strike, insurance claims actually explain very little about Iron Dome's interception rate. The available data does not differentiate between small claims caused by debris or large claims caused by a rocket impact. Without that information, it is impossible to tell if the number of damage claims is

lower for southern Israel because of Iron Dome or because it is more sparsely populated and less dense, thus generating fewer claims even for successful rocket strikes.

Even if this information were persuasive in showing Iron Dome worked, it does nothing to corroborate the IDF's specific claims about an 84 percent success rate in 2012 and a 90 percent success rate in 2014; it would simply show that Iron Dome is working *to some degree*. In sum, Postol's arguments raise important questions but his analysis is insufficient to prove Iron Dome is failing. At the same time, the arguments advanced by Iron Dome's defenders fail to refute Postol's technical claims and rely on unconvincing evidence for which alternative explanations can be found. Therefore, it is not possible to say definitively which side is correct. The IDF's claims about Iron Dome cannot be proven true, but they also have not been proven false. Without additional information, which Israel is currently keeping classified, the true technical efficacy of Iron Dome will remain a mystery.

Peak Iron Dome? Implications of the Future Threat Environment

Of course, Iron Dome's actual technical efficacy is important, but in many ways, what Israelis *believe* about Iron Dome is what truly matters. If the system's skeptics are correct and Iron Dome did not actually work (or work as well as advertised), it would make no difference in terms of the political benefits to the Israeli government as long as Israelis believe that it worked. Belief in Iron Dome's technical efficacy gives Israelis pride, makes them feel safe and protected, and gives the government decision making time and space that it might not otherwise have. While Iron Dome's technical efficacy remains in doubt, there is widespread belief in Israel that it performed spectacularly. This faith not only helped Israelis go about their normal lives during the fighting, it also gave the IDF space to conduct operations under less political pressure and by many accounts saved the Israeli government from having to authorize a massive invasion of Gaza.

This has led to extremely high expectations for Iron Dome among the Israeli public, including the expectation that all population centers in the country should be protected.⁸⁴ Such expectations may prove to be both militarily and politically dangerous in the future. For while Iron Dome may have succeeded technically and certainly succeeded politically during the most recent past two wars in Gaza, the less favorable conditions that will likely characterize Israel's future wars may decrease Iron Dome's technical and political performance. In fact, it is likely that Operation Protective Edge saw Iron Dome at its peak technical and political performance—the system's value will either remain about the same during a future war in Gaza, or decrease dramatically during a future war with Hezbollah or a multi-front war. This has to do mainly with improvements made by Israel's adversaries to their rocket arsenals, improvements that Iron Dome will likely not be able to cope with even if it continues undergoing upgrades.

The Next War with Hezbollah—and Perhaps Others

Over 34 days in 2006, Hezbollah fired 4,228 rockets, mostly Katyushas, for an average of 124 rockets a day. Only around a quarter of the rockets fired actually hit built-up areas, meaning an average of 31 rockets hit built-up areas each day. This killed 53 people, injured over 2,000, and caused massive damage to infrastructure—a huge success for Hezbollah. Doubling down on this

tried-and-true strategy, Hezbollah has expanded its rocket arsenal over the last decade and now possesses upwards of 100,000 rockets, 10 times more than it had in 2006.⁸⁵ Some estimates even put Hezbollah's arsenal at 150,000 rockets, larger than the combined arsenals of most European states.⁸⁶

In addition to this massive increase in the *size* of Hezbollah's rocket arsenal, there has also been an increase in the *quality* of the rockets Hezbollah has been acquiring, though the degree to which this is true is currently unknown. According to media reports and statements from senior IDF officials, Iran, Hezbollah, and Hamas have been conducting joint research into improving the accuracy and lethality of their rockets.⁸⁷ As Hezbollah and Hamas develop and acquire more accurate weapons, they will be able to specifically target critical infrastructure in Israel instead of only having the option of firing indiscriminately and hoping they hit critical infrastructure. Information about how far along Hezbollah and Hamas are in the process of designing and acquiring more accurate rockets is not publically available. It could be that Hezbollah has only acquired a handful of larger, more accurate missiles that it might use against key strategic targets, while the majority of its Katyusha rockets remain crude. But because Hezbollah knows how important improved accuracy will be in its arms race to defeat Iron Dome, Israel must assume that it is committing meaningful resources toward this objective.

Iran, now capable of providing greater assistance to Hezbollah with its land corridor to the Mediterranean across Iraq and Syria, has also signaled that it is assisting Hezbollah in its quest for more advanced weaponry, including rockets with greater accuracy.⁸⁸ Even if this increase in capability is currently limited only to larger missiles that are outside of Iron Dome's purview (and would thus need to be engaged either by Israel's other BMD and air defense systems), the technology necessary to upgrade Katyushas and other crude rockets from statistical weapons to weapons with a modicum of accuracy is becoming cheaper and more ubiquitous with each passing year. It is possible that Hezbollah has already acquired meaningful numbers of more accurate rockets, and if it has not already, it is highly likely that the rate of technological progress will enable Hezbollah to do so in the future.

The IDF also believes there is a high likelihood that a future war will involve multiple fronts, forcing Israel to confront Hamas in the south and Hezbollah in the north at the same time, with perhaps a third front on the border with Syria, a scenario that appears more plausible given the Assad regime's success in Syria's civil war.⁸⁹ Such a conflict could see close to 1,500 rockets fired at Israel *per day*, according to IDF officials—the same amount fired at Israel during the entirety of Operation Pillar of Defense.⁹⁰ These rockets could be fired in salvos of 50 or even 100 rockets.⁹¹

Of course, if Israel were able to quickly destroy many of Hezbollah's rockets and launchers on the ground at the beginning of a war, the smaller number of surviving rockets might be a manageable threat for Iron Dome. Israel has made dramatic increases in its aerial strike capability, claiming the ability to strike in 24 hours the number of targets it struck in Lebanon during the entire 34 day war in 2006.⁹² But it is not a guarantee that Israel's increased capabilities to target Hezbollah's rockets will be enough to overcome the sheer size of Hezbollah's arsenal, coupled with its sophisticated deployment strategy. Hezbollah's rocket arsenal and launchers are dispersed, well-hidden in hardened and urban areas, and mobile. If

history is any guide, targeting rockets and launchers on the ground, even in a massive aerial and artillery campaign, will not be effective at reducing Hezbollah's capacity to sustain large rates of fire against Israel. Israel's air force and artillery corps were unable to stop Hezbollah from continuously firing rockets when its arsenal size was only 13,000. Hezbollah's much larger arsenal, deployed in an even more sophisticated manner, will likely be able to survive Israeli attrition for the duration of the fighting and sustain a large enough rate of fire against Israel to overwhelm Iron Dome and reduce its utility sufficiently to cause political and military costs to Israel. At the very least, Israel must recognize this as a realistic possibility.

These developments present two huge new hurdles for Iron Dome. First, the sheer quantity of rockets, especially if they are fired in such massive salvos, may be so large that Iron Dome's radar will become overwhelmed. The radar works by scanning for rockets and, once it finds one, dwelling on it for a certain amount of time before moving on to scan for other rockets. It then returns to the first rocket again in order to track its trajectory, and repeats this process for all the rockets it finds. As the radar is forced to dwell on more rockets in this cycle, it has less time to scan for new objects and has to wait longer before returning to each rocket, which lessens the quality of the trajectory calculation.

Because the IDF is aware that Hezbollah will attempt salvos of perhaps 100 rockets at a time, they are surely doing everything they can to equip Iron Dome's radar for such a scenario. But all radars have their limits, and given the size of Hezbollah's rocket arsenal, it may be a battle that Iron Dome's radar cannot win. The volume of indiscriminant rocket fire likely to be witnessed in a future war might also force the Iron Dome batteries to expend their magazines of interceptors extremely quickly, either causing the IDF to run out of interceptors or forcing soldiers to constantly reload the launchers, during which time those launchers will be unusable. After firing a huge volley of rockets that depletes Iron Dome's magazines, an adversary could fire a second volley that will face no attrition from Iron Dome.

Second, if a portion of Hezbollah and Hamas's arsenals include guided projectiles, as reports indicate, the percentage of total rockets that Iron Dome will have to intercept will increase. Assume the 1,500 rockets per day estimate for a future war is correct. If all of these rockets are unguided, as they were in all previous engagements, about a fourth of them, 375, would be expected to hit populated areas. If a certain percentage of those projectiles are guided, that number will increase because the guided projectiles have a better than one-fourth chance of landing in a protected area.

Additionally, a guided rocket may require Iron Dome to fire more than one Tamir in order to successfully intercept it. This is because the course corrections of the guided rocket will complicate the radars' tracking and provide less time to calculate an intercept point.⁹³ Any terminal guidance on the projectile can also interfere with the Tamir's ability to detonate in close enough proximity to the incoming warhead in order to destroy it.⁹⁴ Equipping short-range rockets with cheap GPS guidance systems is relatively easy. It would increase the cost of each rocket substantially but would still be far cheaper than each Tamir interceptor. Hamas and Hezbollah would not need to equip all of their rockets with such guidance systems in order to change the equation with Israel dramatically. If only a small percentage of their rocket arsenals contain guided rockets, it is not difficult to imagine various tactics wherein they mix and match both

types of rockets in order to defeat Iron Dome. They might fire huge volleys of unguided rockets to deplete Iron Dome's magazines and then fire guided rockets at critical targets that would be temporarily defenseless. They might also fire a salvo comprised mostly of unguided rockets with only a few guided rockets mixed in, increasing the chances that the guided rockets get through. Such tactics can become even more complex if medium-range missiles and cruise missiles are added to the mix.

Potential Consequences of Iron Dome's Degraded Performance

The massive increase in the quantity of the rockets pointed at Israel, coupled with the increase in the quality of some of those rockets, calls into question the viability of Iron Dome in large-scale conflicts. If Iron Dome is called upon to perform in combat under less favorable conditions than existed in 2012 and 2014, and it fails to deliver results in accordance with the Israeli population's expectations, what might the consequences be? Despite some IDF officials attempting to lower expectations about Iron Dome,⁹⁵ Israelis now expect the population to be protected, often to an unrealistic degree. This presents three main problems. First, complacency about the rocket threat—under the belief that Iron Dome works exceptionally well and will continue to do so in future wars—can cause reckless behavior, including ignoring the sirens alerting people to seek shelter. This has already happened, as some Israelis remained outside during rocket attacks in attempts to take pictures of Iron Dome in action. The benefit of feeling protected, which allows for some degree of normalcy during wartime, is a good thing, but if taken too far it can degrade the civil defense necessary to save lives.

Second, if the combination of larger raid sizes and guided rockets is used to target IDF bases, the government may decide to prioritize protecting those bases at the expense of the population. The IDF relies heavily on its air force, and ensuring that fighter jets can take off and land without interruption will be critical for any future war effort. Because Iron Dome batteries are a limited resource, decisions must be made about how to allocate that resource when the demand is greater than the supply. If there simply aren't enough Iron Dome batteries to provide protection to military and critical infrastructure while also protecting population centers, the IDF will be forced to pull coverage from population centers. This is likely to have political ramifications. If the level of damage that befalls the population centers after coverage was withdrawn is severe, anger at the government could cause inquiries or even the shattering of the ruling coalition as parties blame each other for electoral gain. It is extremely difficult for any government to take away benefits that the population has already received.

Lastly, what effect might Iron Dome's degraded performance have on the perception of victory in both Israel and the Arab world? Iron Dome helped Israelis conceptualize the outcome of the last two wars as victories for Israel because Hamas's main threat had been neutralized. Because Israelis place so much pride and faith in Iron Dome, if the system performs below expectations (or is exposed as not working as well as previously believed), Israelis might have a harder time believing they achieved victory during a future war. Hamas and Hezbollah certainly understand the role that Iron Dome has played in the Israeli narrative of its wars and would be quick to exploit Iron Dome's perceived or real weaknesses for propaganda purposes and to claim to its own people that it achieved victory. Parades in Beirut and Gaza City trumpeting the success of the crude rocket over Israel's sophisticated defense system are not hard to imagine, even if Iron Dome achieves, say, a 60 percent success rate instead of a 90 percent success rate. Because

Israelis expect better, anything substantially less than 90 percent will be embarrassing. For Hamas and Hezbollah, any degradation of Iron Dome's success rate could be claimed as a victory attributable to their perseverance and successful rocket-launching tactics.

Conclusion: Iron Dome's Role in Israel's Defense Strategy

Because crude rockets will always be cheaper and more plentiful than the sophisticated interceptors needed to counter them, rocket defense will be an arms race that the defender is eventually going to lose. To be sure, while Hamas and Hezbollah have been busy growing their arsenals and devising tactics to defeat Iron Dome, the Israelis have been working to keep up. Israeli officials often tout the upgrades that Iron Dome has received over the years. The Israeli Air Force's Aerial Defense Division commander claimed in 2016 that, "other than the name, everything [about Iron Dome] is completely different."⁹⁶

Israel has also signaled recently that it wishes to expedite production of additional Iron Dome batteries to meet the evolving threat.⁹⁷ These upgrades may help keep pace with Hamas's arsenal given that Hamas is smaller and less capable than Hezbollah. Israel and Egypt also maintain a blockade of the Gaza Strip to prevent Hamas from smuggling additional rockets into the territory. But against 150,000 rockets in the hands of a wealthier and more capable enemy like Hezbollah, which faces no blockade from Israel, upgrades to Iron Dome are unlikely to keep up. Therefore, it is possible that Israel has reached "peak Iron Dome," wherein the system's performance may increase or decrease slightly in future engagements with Hamas, but will almost certainly perform poorly in a future conflict with Hezbollah or a multifront war, which IDF officials believe is a likely scenario.

This is not to say that Iron Dome was not worth the cost and should not have been invented. It worked well, either technically, politically, or both, under the unique set of conditions seen over the past decade. But expectations about Iron Dome must be brought in line with reality. Having an unrealistic expectation of protection from rockets during future wars could prove deadly for civilians and costly to Israel politically. The Israeli government must begin the process of explaining to the population the conditions of a future war that will make protection of the entire country impossible. Either the IDF will need the batteries for the war effort or the system will simply be overwhelmed by the larger raid sizes fired into Israel. If Israelis understand that Iron Dome will not provide such coverage, they will take the civil defense measures more seriously and will be less likely to see any of Iron Dome's failures as a failure of the war effort overall.

Israel should keep Iron Dome and continue to upgrade it, mostly for use in conflicts with Gaza and to intercept the handful of rockets that militants occasionally fire into Israel during peacetime—essentially taking these "cheap shots" off the table as an effective terror weapon. It may also have a role in defending Israeli offshore oil drilling platforms.⁹⁸ But it should not be expected to defend Israel if and when the next war with Hezbollah or a regional war comes. Its role must be understood as limited by both the people and the government.

If Israel goes into the next war with its current mindset about Iron Dome, the disparity between Israel's expectations and reality may result in a perception of failure after the fighting stops.

Hezbollah, Hamas, and others will claim that its rockets overcame Israel's miracle weapon. They may even benefit from an Israeli ground invasion necessitated by Iron Dome's degraded performance, which would force Israeli soldiers into densely populated and booby-trapped territory where Hamas and Hezbollah fighters can confront them more easily. If large quantities of rockets strike Israeli population centers, Israel may feel compelled to use even heavier military force, creating a diplomatic crisis for Israel and a humanitarian crisis for the residents of Lebanon, Gaza, and Syria.

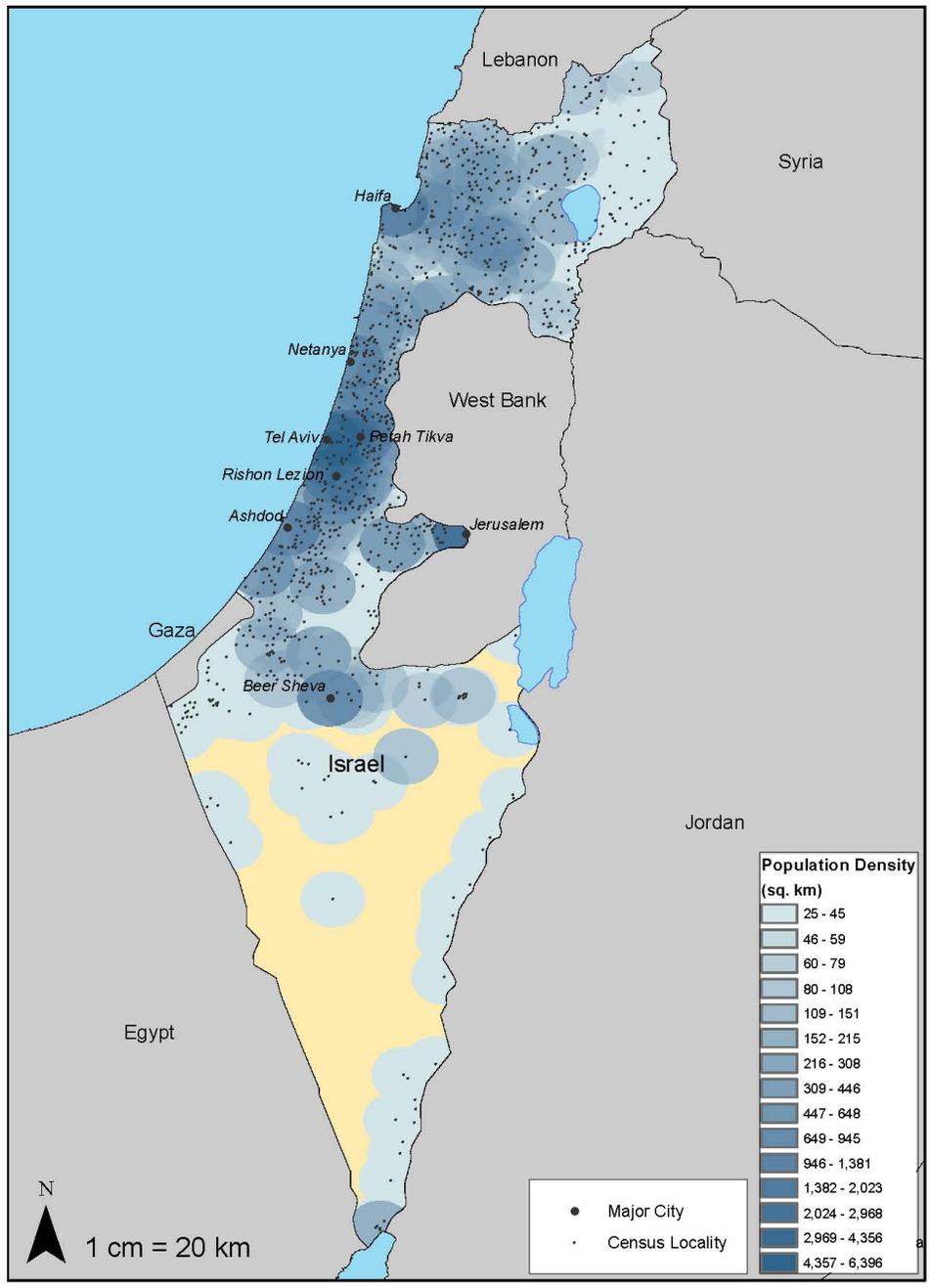
Hopefully, these theoretical questions about Iron Dome's performance in a future war will never be answered and deterrence between Israel and its adversaries will hold for the foreseeable future.⁹⁹ The tragic consequences of deterrence failure for the innocent on all sides are painful to imagine. But in an unstable region, the possibility of another war between Israel and its adversaries is a real, and growing, possibility. Israel, and Iron Dome's advocates around the world, would be wise to temper their expectations about the system's performance given the very real chance that the next war produces conditions so unfavorable for rocket defense that Iron Dome becomes viewed as a failure.

About the author

Ari Kattan is a Policy Analyst at Science Applications International Corporation (SAIC), where he supports the Defense Science Board. The opinions expressed in this paper are the author's and do not necessarily represent the views of SAIC or its government clients. He thanks Catherine McArdle Kelleher and Jaganath Sankaran for providing helpful feedback for this paper.

Appendix A: Israel's Population Density in 2014¹⁰⁰

Population Density of Israel, 2014



¹ Ariel Levite and Slomo Brom, "From Dream to Reality: Israel and Missile Defense," in *Regional Missile Defense from a Global Perspective*, ed. Catherine McArdle Kelleher and Peter Dombrowski, (Stanford: Stanford University Press, 2015), 145.

² For more on Israel's defense doctrine, see, inter alia, Yoav Ben-Horin and Barry Posen, *Israel's Strategic Doctrine* (Washington, DC: RAND, September 1981), <https://www.rand.org/content/dam/rand/pubs/reports/2007/R2845.pdf>; and Dima Adamsky, *The Culture of Military Innovation: The Impact of Cultural Factors on the Revolution in Military Affairs in Russia, the US, and Israel* (Stanford: Stanford University Press, 2010), 112-113.

³ Abraham Rabinovich, *The Yom Kippur War: The Epic Encounter that Transformed the Middle East* (New York: Schocken Books, 2004), 457-458.

⁴ Levite and Brom, 139.

⁵ F. Gregory Gause, III, *The International Relations of the Persian Gulf* (Cambridge: Cambridge University Press, 2010), 75-83.

⁶ Dennis M. Gormley, *Missile Contagion: Cruise Missile Proliferation and the Threat to International Security* (Annapolis: Naval Institute Press, 2008), 17.

⁷ Levite and Brom, 140-141.

⁸ After Israel demonstrated its complete air superiority in the Yom Kippur War and again in 1982 over the skies of Lebanon, Arab armies realized that ballistic missiles were the only way to threaten the Israeli homeland. They began building up their ballistic missile arsenals in an attempt to offset Israel's aerial strength. See Gormley, 29-34. Iran also embarked on a large-scale ballistic missile development program during this time, first acquiring Scud missiles from Libya in 1985 and then pursuing domestic development with assistance from North Korea. Iran now possesses the largest and most active ballistic missile program in the Middle East, with both short- and long-range missiles capable of hitting targets throughout the Gulf and even southern Europe. Exact estimates are not available, but it is believed that Iran possesses over 1,000 missiles with ranges varying from 150 km to 2,000 km. See Yoel Guzansky and Yiftah S. Shapir, "Iran Goes Ballistic," *Middle East Quarterly* (Winter 2015), http://www.meforum.org/4911/iran-goes-ballistic#_ftn1.

⁹ Gormley, 18.

¹⁰ Israel's invasion and occupation of Lebanon was initiated for several complicated reasons. A detailed account of this history can be found in Chapter 11 of Benny Morris's *Righteous Victims: A History of the Zionist-Arab Conflict, 1881-2001*, (New York: Random House, Inc., 2001).

¹¹ "Hezbollah's rocket force," *BBC News*, July 18, 2006, http://news.bbc.co.uk/2/hi/middle_east/5187974.stm.

¹² Jean-Loup Samaan, "Another Brick in the Wall: The Israeli Experience in Missile Defense," *U.S. Army War College Strategic Studies Institute*, April 2015, 17, <http://www.strategicstudiesinstitute.army.mil/pubs/display.cfm?pubID=1261>.

¹³ Matt M. Matthews, *We Were Caught Unprepared: The 2006 Hezbollah-Israeli War* (Fort Leavenworth, KS: Combat Studies Institute Press, 2008), 8-9, <http://usacac.army.mil/cac2/cgsc/carl/download/csipubs/matthewsOP26.pdf>.

¹⁴ Ibid.

¹⁵ Amir Kulick, "Hizbollah vs. the IDF: The Operational Dimension," *Strategic Assessment* 9, no. 3 (November 2006): 29-30, http://www.inss.org.il/uploadImages/systemFiles/AdkanEng9_3_Kulick.pdf.

¹⁶ William J. Broad, "U.S. and Israel Shelved Laser as a Defense," *New York Times*, July 30, 2006, <http://www.nytimes.com/2006/07/30/world/middleeast/30laser.html>.

¹⁷ Ibid.

¹⁸ Ibid.

¹⁹ Levite and Brom, 143.

²⁰ Matthews, 16-18.

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