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# Design Parameters for Small Engines based on Market Research

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## Abstract

Small internal combustion engines outperform batteries and fuel cells in regards to weight for a range of applications, including consumer products, marine vehicles, small manned ground vehicles, unmanned vehicles, and generators. The power ranges for these applications are typically between 1 kW and 10 kW. There are numerous technical challenges associated with engines producing power in this range resulting in low power density and high specific fuel consumption. As such, there is a large range of engine design solutions that are commercially available in this power range to overcome these technical challenges. A market survey was conducted of commercially available engines with power outputs less than 10 kW. The subsequent analysis highlights the trade-offs between power output, engine weight, and specific fuel consumption. These engines are analyzed to show the benefits and disadvantages of different engine design parameters including fuel type, number of strokes per cycle, number of cylinders, intake pressure, and cooling strategy. A Pareto frontier analysis is conducted to identify the top performing engines based on the output power and the total power system weight. Recommended designs are presented for different ranges of output powers.

## Introduction

The last three decades have seen a significant growth in internal combustion engine development especially in regards to increasing engine performance and decreasing specific fuel consumption (SFC) [1]. Though the bulk of these advancements are for larger automobile engines, advances have been made on smaller engines as well. These advancements are beneficial because smaller engines will continue to play a large role in different military and commercial markets [2]. While a significant portion of the energy market is moving towards batteries, several markets have turned to small engines as a lightweight solution for providing reliable power for extended durations [3].

These markets include small manned and unmanned vehicles, consumer products, marine applications, and generators. A common thread for these markets is that they deal with portable systems where the weight is a key design parameter. If weight was not critical, these applications could simply use batteries and not deal with the complications associated with an internal combustion engine.

Since weight is critical for these applications, it is often necessary to approximate the total power system weight early in the design process. Approximations are readily available for large engines based on automotive databases and practices; however, these approximations do not readily scale down for smaller engines [4]. This paper sets out to develop these approximations and uncover general trends in the small engine market through extensive market research. This market survey captured the dry weight, power output, and SFC of numerous small engines.

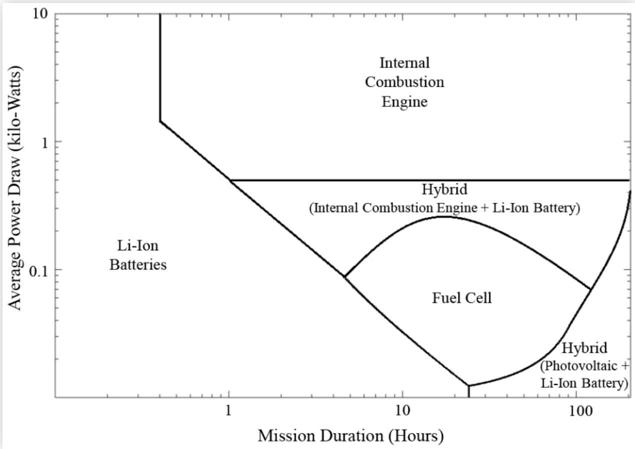
The collected data was further analyzed to identify the lightest weight power systems over a given range of power outputs. The power system weight included the weight of the fuel for this analysis. This analysis was used to identify engine design guidance as a function of the required power.

## Overview of Low-Power Technologies (<10 kW)

Small engines have traditionally competed with fuel cells, batteries, and photovoltaics to power devices that require less than 10 kW [5]. Since these power systems are typically for mobile or man-portable application, weight is a key design parameter when selecting the appropriate power solution.

An analysis of engines, batteries, fuel cells, and photovoltaics was conducted to determine the lightest weight solution over a range of powers and durations. This analysis was performed for a robotic application; however, the overall trends can be expanded to other markets as well. The analysis used standard design values and current development trends for each technology to estimate the power system weight [6, 7, 8, 9] for a given power and energy requirement. The power

**FIGURE 1** Map of lightest weight power solution for power draws between 10 W to 10 kW for durations between 1 minute and 200 hours.




system weight included the weight of the power source, accessories (e.g. alternator), and any necessary fuel. These values were compared between the different technologies to determine the lightest weight option. This analysis focused on a power range from 10 W to 10 kW and a duration from 10 minutes to 200 hours. The results are plotted in Figure 1.

Figure 1 shows that a battery solution is optimal for shorter durations and powers below 1 kW. These applications include mobile phones, remote controls, flashlights, and some power tools. However, as duration increases past an hour, and as power demand is greater than 1 kW, an engine solution is optimal. Additionally, for similar mission durations, but lower powers, a hybrid system is optimal, where an engine recharges a battery bank. Fuel cells and photovoltaics are the lightest weight solution for power draws less than 200 W and durations greater than 10 hours.

Despite being the lightest weight solution over a large range of powers and durations, small engine usage has been limited by several major design challenges. The largest challenge is associated with their inherently low efficiencies [4]. Efficiency losses through heat transfer and friction scale with the surface area; meanwhile, the power output scales with the volume. Therefore, as the volume decreases, the proportional losses due to friction and heat transfer increase. These losses result in a lower efficiency, which equates to a higher SFC. Since this issue is fundamentally a geometry issue, recent developments in novel engine geometries allow for decreases in SFC. Many of these novel engine geometries are being applied to rotary engines [10].

A second major design challenge is associated with the fabrication tolerances of parts. Quite simply, small engines require smaller, more accurate parts. As such, design tolerances are much more critical for small engines than for larger engines, especially in regards to sealing. Tight tolerances result in difficulty in fabrication and increased cost [11]. However, advances have been made in regards to manufacturing processes for smaller electrical-mechanical devices; these advances have been translated into the development of small engines [12].

A third major design challenge is associated with the engine exhaust [13]. The size and cost constraints on small engines often result in the exclusion of mufflers. Additionally, emission requirements from small engines are less regulated than they are for larger automotive engines. Therefore, after-treatment technology, such as catalytic converters are often excluded. The noise and emissions create limitations on the use of these engines for certain applications, especially those that are used indoors. These issues are somewhat mitigated through new advances in after-treatment and active noise cancellation [14].

## Commercial Markets for Small Engines

As shown in Figure 1, small engines are the lightest weight power solution for applications that require portable power greater than 1 kW for durations greater than a couple of hours. A large number of applications fall into this range of power and mission durations.

The markets for small engines are limited to those that have mobile applications. Although numerous non-mobile applications, such as air conditioners, fall within these power and duration ranges, those devices can simply be plugged into the grid, reducing the need for a self-contained power source. The market survey found five main categories of portable applications for small engines.

The first market is unmanned vehicles, which include remote control aircraft and ground vehicles. Though these markets have traditionally used batteries, increased range and power requirements have necessitated the use of small engines [3]. These engines have small alternators to provide electricity for electronics; however, the bulk of the power goes into turning wheels or producing thrust. A subset of unmanned vehicles is sophisticated military unmanned aerial systems (UASs), which are seeing increasing usage over the last decade. Many of the smallest, lightest weight engines have been developed for UASs.

Small manned ground vehicles are the second market for small engines. Though most automobiles require in excess to 50 kW, smaller, single-passenger vehicles can require less than 10 kW. This market includes scooters, riding lawn-mowers, and go-carts. Additionally, some hybrid vehicles use low power engines as "range extenders" to recharge the batteries. This market is increasing and the engine technologies are advancing due to the increased usage and regulation of hybrid vehicles and scooters.

Marine applications, including small recreational boats, are the third market that use small engines. Boats typically require significantly less power than ground vehicles, so smaller boats have engines that produce less than 10 kW. Since battery usage on boats is somewhat limited due to safety reasons, marine applications have historically used small engines; this trend is expected to continue. Hence, the marine engine market is fairly well developed.

The fourth market is consumer products, which consists primarily of lawn mowers and larger power tools.

Though there are battery-powered variants of these devices, higher power and duration requirements often necessitate an internal combustion engine. As batteries become more power and energy dense, the use of engines is decreasing. However, high-power commercial tools, which are used constantly through a work day, will still require small engines.

Portable power generators are the fifth major market that use small engines. Generators are used for providing power in remote locations or as a backup power source. Critical household devices require more than 1 kW and less than 10 kW, so small engines are commonly used as the power source in generator sets. Batteries and fuel cells are starting to enter into these markets; however, small engines dominate this market.

## Small Engine Designs

The diversity of the engine markets result in a large range of engine design requirements. For example, the generator market requires very efficient power conversion. Meanwhile, the unmanned vehicle market is often willing to sacrifice efficiency to make the engine lighter weight. And the consumer product market is willing to accept heavier, less efficient engines to minimize cost. Since there is a wide range of system requirements, there is a wide range of engine designs. Broadly, these engine designs can be categorized as being one of the following categories: 2-stroke, 4-stroke, and rotary.

A 2-stroke engine follows a simple engine cycle that couples the air intake and exhaust with the compression and expansion strokes. Combining intake with compression results in inefficiencies in both processes. Additionally, the combination of these strokes results in a significant decrease in efficiency due to scavenging losses during the gas exchange process. These inefficiencies compound to make 2-stroke engines fairly inefficient. The inefficiencies are somewhat offset by the engine producing power on every rotation. Additionally, 2-stroke engines are simple and require few parts. As such, they tend to be lightweight and low cost [15].

Though there are numerous exceptions, 4-stroke engines are typically more efficient, more complex, heavier, and more expensive than 2-stroke engines. A 4-stroke engine separates the intake and exhaust processes from the compression and expansion strokes. As such, the engine avoids the issues of a 2-stroke engine and can be tuned in such a way to make the engine much more efficient. However, the increased efficiencies are slightly reduced by the engine only producing power on one of every two rotations, increasing losses to friction [16].

The rotary engine is a variant of the 4-stroke engine that uses an eccentric rotary design as opposed to a traditional reciprocating piston design. These engines are able to attain a low SFC while remaining compact and lightweight. However, small rotary engines typically have sealing issues which require close tolerances in the design. As such, they are expensive and their use is limited [17].

## Market Survey

A market survey was conducted on small engines with power outputs between 1 kW and 10 kW. This range was selected for mobile application where weight and power output are two key design parameters. The goal of the market survey was to develop a better understanding of the relationship between weight and power and to build correlations.

The market research involved contacting and getting specification sheets from over 100 different engine companies. These companies were from eighteen different countries and were for the five markets discussed in the earlier section. Over 500 engines were identified; however, since multiple companies would sell the same engine under different names, this number was reduced to 284 unique engines. These engines were identified and classified. Note that due to the proprietary nature of certain engines, the names of the companies and engines are not included in this paper.

The survey focused on the weight and power output of the engine. The power output was defined as the maximum steady-state power that the engine could produce. The weight included all necessary accessories for the engine to operate and produce the required power. Since fuel weight can quickly exceed the dry weight of the engine for multi-hour missions, SFC was another key parameter included in the survey. SFC was typically not included on the specification sheets, so it was estimated based on the engine technology; these estimations are shown in a later section. Additionally, the market survey also collected date on the engine type (e.g. 4-stroke, 2-stroke, Wankel), number of cylinders, fuel type, cost, and cooling strategy.

## Results: Engine Types

As shown in Table 1, the selection of small engines were split fairly evenly between 2-stroke and 4-stroke engines. Only a few rotary engines were identified. The cost of the rotary engine makes it prohibitively expensive for many consumer markets. However, several rotary engines were being developed for military applications that are willing to accept a higher cost to achieve a higher power density and lower SFC.

As expected, the 2-stroke engine dominated markets where weight was critical, especially unmanned vehicles. Approximately 77 percent of engines identified for unmanned vehicles were 2-stroke engines. The remaining 23 percent were rotary engines and 4-stroke engines, the majority of which were used for larger military UASs.

The 4-stroke engines dominated markets where fuel consumption is critical and where emissions are regulated.

**TABLE 1** The distribution of engine type by market

| Market | 2-Stroke | 4-Stroke | Rotary |
|---|---|---|---|
| Consumer Products | 14% | 86% | 0% |
| Generators | 0% | 100% | 0% |
| Marine | 11% | 89% | 0% |
| Unmanned Vehicle | 77% | 19% | 4% |
| Manned Ground Vehicle | 8% | 92% | 0% |
| **All Markets** | 41% | 56% | 2% |

In particular, all of the engines used in generators were 4-stroke. Additionally, the majority of consumer products, marine, and manned ground vehicle engines were 4-stroke as well. These applications are also less weight constrained than unmanned vehicles.

## Results: Number of Cylinders

The engines in the market survey can be broken down into being 1-cylinder or multi-cylinder. The simplicity of a 1-cylinder engine makes it the favored engine for many applications, with over 75 percent of the identified engines being 1-cylinder. Additionally, for a given displaced volume (which scales with power output), a 1-cylinder has less surface area than a 2-cylinder engine, hence reducing the heat transfer and friction losses.

However, multi-cylinder engines have advantages in regards to balancing. The cylinders can be aligned and timed in such a way to reduce the overall vibration of the engine. Additionally, 4-stroke engines work more reliably and produce more continuous power when they use a multi-cylinders, since each cylinder only produces power once every two rotations.

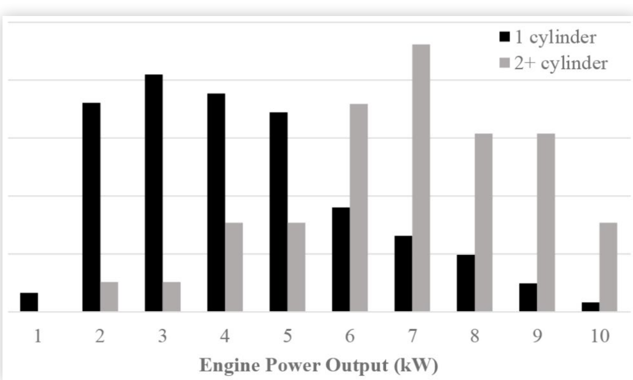
Figure 2 shows a histogram of power distributions for 1-cylinder and 2+ cylinder configurations. As expected, 1-cylinder engines are more commonly used for lower outputs on the range of 1-5 kW. The higher power outputs, 6-10 kW, use multi-cylinder engines. The market survey found that the bulk of the multi-cylinder engines consisted of cylinders that the manufacture used in their 1-cylinder variant.

## Results: Cost

Cost data was not available for many of the engines identified in the market survey. However, from those that included cost data, several general trends were identified.

First, the cost for engines in unmanned vehicles had a bimodal distribution. The lower cost engines are intended for hobbyist and were on the order of a few hundred dollars. The higher cost engines were intended for military applications. These typically had higher power densities and lower SFC.

**FIGURE 2** Histogram of power distributions for single-cylinder and multi-cylinder configurations based on market survey.




The cost for the engines ranged on the order of tens of thousands of dollars.

Second, engine costs for consumer products were typically the lowest cost, since these engines are mass produced and go into cost-sensitive devices. In order to keep the cost down, these engines were typically 1-cylinder.

Third, engines for marine and manned ground vehicle applications were more expensive than other markets, aside from military UASs. Since these engines are used in manned vehicles, they are subject to additional design constraints in regards to emissions and safety. These additional constraints result in additional cost.

Fourth, the cost of engines did not scale with the power output. Often lighter-weight, lower-power engines cost more than a higher-power variant. However, the cost for 4-stroke engines were typically more than that of 2-stroke engines; the cost for a multi-cylinder engine was more than that of a single-cylinder engine; and liquid-cooled engines were more expensive than air-cooled engines.

## Results: Other Design Parameters

The market survey identified a number of other engine design parameters including fuel type, cooling techniques, and boosting strategy. The engines in the survey all used similar designs in regards to these parameters with the occasional outlier. The majority of the engines ran on 87-octane gasoline, used an air-cooling strategy, and were naturally aspirated.

The majority of the engines ran on standard 87-octane unleaded gasoline. This fuel is readily available and higher octane fuels are not needed because small engines are not knock limited. Most of the 2-stroke engines blend the gasoline with 2-5 percent lubrication oil since the fuel is injected through the cylinder walls. Due to the heavy weight associated with diesel accessories, diesel engines were only used for heavier engines, namely larger generators. Additionally, several engines that are designed for military UAS vehicles run on JP-8, a variant of kerosene with properties similar to diesel fuel.

Cooling strategies are critical for small engines because their low efficiencies manifest themselves as large thermal losses [18]. The majority of small engines are air-cooled through forced convection across fins. In particular, engines on manned and unmanned vehicles align cooling fins with the direction of vehicle motion to maximize convection. Stationary devices, such as generators, use fans to force air over the engine body to remove heat. Marine engines take advantage of being submerged in water and use that water as the heat transfer medium. Less than 3 percent of the engines were liquid cooled, which were only used for unmanned vehicle engines that required long durations. The use of liquid cooling increases the reliability of the engine, though it does greatly increase the weight.

Almost all of the engines are naturally aspirated with less than 2 percent of the engines being boosted through turbocharging or supercharging. Small engines are concerned with maintaining a low weight, and a turbocharger or a supercharger would weigh more than the engine itself. Additionally, small compressors have similar parasitic losses to small engines, hence compounding the inefficiencies. Boosted engines were used only on those that ran on heavy fuels, which required boosting to vaporize the fuel [4].

## Engine Weight Versus Power Output

An analysis was conducted to capture the weight of the engine as a function of power output. Figure 3 shows the distribution of data points for weight as a function of the power output. Though significant scatter, the general trends shows that the weight of the engine increases with the power output.

Each of the five different markets were fitted separately to develop linear approximations for the engine weight as a function of power. The coefficients to the linear approximations are given in Table 2, where the weight of the engine can be calculated by:

$$Weight = Offset + \frac{power}{specific\ power} \tag{1}$$

The weights include the balance of plant, which is substantially different for the each application. For example, the engines for manned ground vehicles include significantly more after-treatment than their unmanned counterparts. Many of the engines additionally require alternators to produce electricity from mechanical energy. The weight of the alternator can readily outweigh other components, especially for the generator market, where all the mechanical energy is converted into electricity.

The $R^2$ values listed in Table 2 show the "goodness" of each linear fit, where a lower $R^2$ value means that the collected data better matches the linear approximation. Note that though Figure 3 appears to have a fairly tight fit between the unmanned vehicle data and the approximation, there is still significant scatter that is not seen due to the scaling of the y-axis. The more developed industries—marine, generators,

**FIGURE 3** The distribution of data points for weight as a function of power requirement for small engines in different markets.

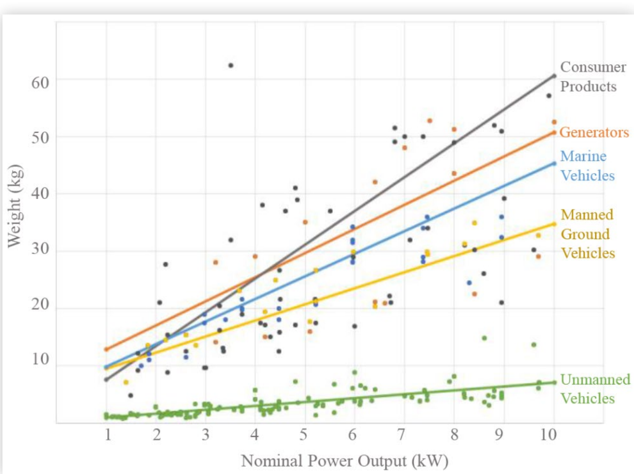





**TABLE 2** Linear approximations for the engine dry weight as a function of power output for different markets

| Market | Specific Power (kW/kg) | Offset (kg) | $R^2$ Value |
|---|---|---|---|
| Unmanned Vehicle | 1.46 | 0.2 | 0.31 |
| Manned Ground Vehicle | 0.36 | 6.6 | 0.67 |
| Marines | 0.24 | 5.8 | 0.14 |
| Generators | 0.26 | 8.6 | 0.12 |
| Consumer Products | 0.17 | 1.6 | 0.14 |

and consumer products—all have very low $R^2$ values since there is not vast differences between the different engine models. However, the less established industries, unmanned vehicles and manned vehicles, have significantly more scatter due to the broad range of different engine designs.

The unmanned vehicles have the highest specific power and lowest offset due to the fact that the majority of these engines are used on small aircraft which are weight constrained. A heavier engine would necessitate additional power for flight, hence creating an undesirable feedback loop. Therefore, the engines are made with the intent of reducing weight. For example, since they are used on moving flight, the engines are cooled through forced air convection, reducing the amount of cooling accessories required. Additionally, the engines have very small alternators, relying on the mechanical work extracted from the engine to turn propellers and drive transmissions.

A high specific power was found to correspond with higher costs. The highest cost engines are those associated with military unmanned vehicles, which must achieve very demanding power densities. Meanwhile, the lowest cost engines are those associated with consumer products, which tend to have a very low power density.

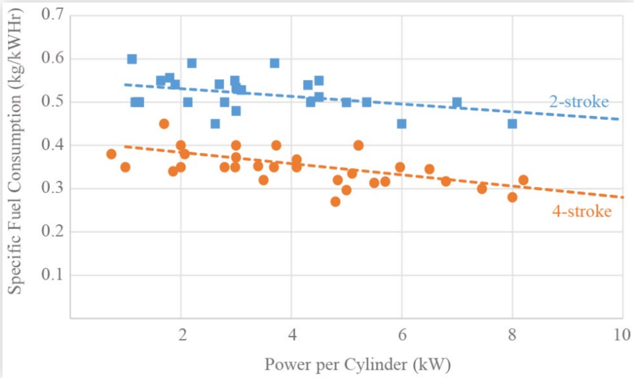
Engines for small manned vehicles, generators, and marine engines all have similar specific powers and offsets. Though the accessories required for these three markets are fairly different, they are comparable in weight. For example, the weight of the alternator in the generator is comparable to the after-treatment required for a manned ground vehicle.

## Specific Fuel Consumption Versus Power Output

Only 20 percent of engine specification sheets include the SFC or efficiency. The SFC that was included on the specification sheets is normally the fuel expenditure rate to produce power at maximum brake torque timing. The available data was used to build an approximation for the SFC of engines that did not include a value on their specification sheet.

Though the SFC is based on a number of engine parameters, an analysis of variance found that the primary variables of significance was the power output divided by the number of cylinders. These results make sense because as discussed previously, 4-stroke engines tend to be more efficient than 2-stroke engines, and hence have a reduced SFC. Cylinder size also plays a significant role; as the cylinder gets smaller, the surface area

**FIGURE 4** Specific Fuel Consumption with approximations as a function of power per cylinder




to volume ratio increases. Friction and heat transfer scale with surface area, while power output scales with volume. Therefore, as the cylinder gets smaller, the efficiency decreases and the SFC increases. The size of the engine cylinder(s) scales with the power output divided by the number of cylinders.

Figure 4 shows an approximation for SFC as a function of power per cylinder for 2-stroke engines and 4-stroke engines based on the data collected in the market survey. As expected, 4-stroke engines have a lower SFC than 2-stroke engines. Additionally, as the cylinder size increases, the SFC decreases. The linear fit was used to create a correlation that could be used to approximate the SFC for engines that did not include that value on the spec sheet.

## Lightweight Engine Design Practices

A Pareto frontier analysis identifies optimal solutions over a multi-variable design space. This analysis technique was applied to the market survey data to identify engine technologies with the lowest system weights for given power ranges. Note that the system weight includes the engine itself, the balance of plant, and 10 kWHr of fuel. The fuel weight allows the analysis to capture the SFC of each engine. By plotting the values, the Pareto frontier can be readily determined as shown by the dotted red line in Figure 5. The associated engines that were selected are shown in Table 3.

All of the selected engines are used in unmanned vehicles, with several of them specifically being military UAS engines. As discussed earlier, military applications are often willing to accept higher costs to achieve higher power densities and lower fuel consumptions. Lower SFC can result in longer mission durations for a given weight, a desirable outcome for many military use cases.

The analysis found that for smaller engines, the weight of the fuel plays a substantial role; hence it is important for the smaller engines to have a low SFC. For example, the fuel accounts for 75 percent of the total weight of Engines A and B. Therefore, a small decrease in SFC will significantly reduce weight. The larger engines naturally have a higher dry weight. Accordingly,

**FIGURE 5** Pareto Frontier analysis to identify the lightest weight engine solution for a given power output. The weight of the power system includes the engine, accessories, and 10 kWHr of fuel.

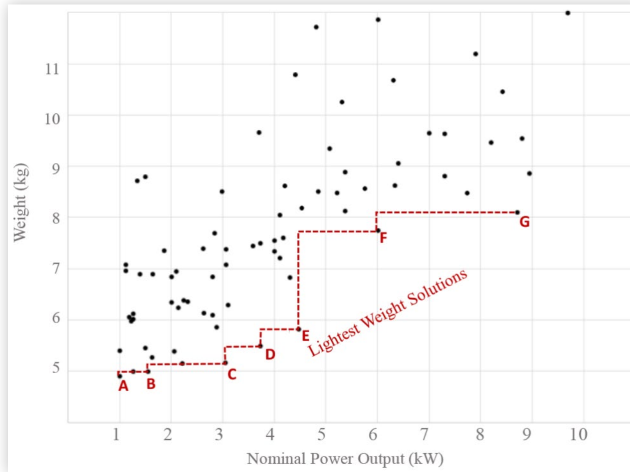



**TABLE 3** Optimal engines identified by the Pareto Frontier analysis displayed in Figure 4.

| # | Power (kW) | Dry Weight (kg) | SFC (kg / kWHr) | Fuel | Number of Cylinder | Number of Strokes | Market |
|---|---|---|---|---|---|---|---|
| A | 1.0 | 1.4 | 0.35 | Gas | 1 | 4 | UAS |
| B | 1.5 | 1.5 | 0.35 | Gas | 1 | 4 | RC Aircraft |
| C | 3.1 | 1.5 | 0.37 | Gas | 1 | 4 | RC Aircraft |
| D | 3.7 | 2.4 | 0.31 | Heavy Fuel | Rotary | Rotary | UAS |
| E | 4.5 | 2.5 | 0.33 | Gas | 1 | 4 | RC Aircraft |
| F | 6.0 | 3.8 | 0.41 | Gas + Oil | 2 | 2 | UAS |
| G | 8.9 | 3.1 | 0.45 | Gas + Oil | 2 | 2 | RC Aircraft |

the 10 kWHr fuel weight becomes less of an issue as the engines get larger. For the larger engine, the goal is to maximize the engine dry weight, even at small sacrifices to efficiency. As such, the smaller engines tend to be 4-stroke engines, which have a lower SFC, while the largest engine is a 2-stroke with a higher SFC.

The outlier for the engines is Engine D which is a heavy-fuel rotary engine. The engine was designed for military UAS applications, hence the need for it to run on heavy fuels. The use of the Wankel cycle allows for the engine to have a low SFC, even at low power outputs. The low SFC makes this engine the optimal solution for a narrow range of powers, approximately 3.1 kW to 3.7 kW. However, since the power density of the engine is significantly less than traditional engines, 2-stroke engines work better at lower powers, and 4-stroke engines work better at higher powers. There is potential for rotary engines to dominate the lower power ranges due to their low SFC. However, many low power applications will not use rotary engines due to their cost.

## Conclusions

Internal combustion engines were compared to batteries and fuel cells to determine the lightest weight power solution over a range of power and mission times. The engine solution was found to be lighter than batteries or fuel cells for applications requiring more than 1 kW for mission durations greater than 1 hour. As such, a number of small engines are available that range from 1 kW to 10 kW for a range of applications including consumer products, generators, small manned ground vehicles, marine vehicles, and unmanned vehicles. There are numerous technical challenges associated with developing engines in these low power ranges; in particular, small engines typically have low specific fuel consumptions and low power densities.

A market analysis identified methods that companies use to overcome these technical challenges. The market data found trends between power output and engine weight for each consumer application. The analysis presented approximations for the engine weight based on the desired power output for each market. These approximations can be used by engineers early in the design process to estimate the power system weight.

A Pareto Frontier analysis was conducted to identify the lightest weight powers system, defined as the engine, accessories, and 10 kWHr of fuel. The selected engines were analyzed to identify optimal design techniques. The analysis found that for power outputs below 5 kW, specific power can be sacrificed for a lower specific fuel consumption; hence, an optimized 4-stroke engine is optimal due to its lower specific fuel consumption. However, for power outputs greater than 5 kW, the dry engine weight plays a more critical role, hence a lightweight 2-stroke engine with a reasonable specific fuel consumption is optimal.

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## Definitions/Abbreviations

**SFC** - Specific fuel consumption

**UAS** - Unmanned aerial system

**unmanned vehicle** - Autonomous or remote-controlled vehicle

**manned ground vehicle** - Vehicle used for moving a passenger (e.g. scooter, go-cart)

**marine vehicle** - Vehicle used to move over bodies of water

**consumer products** - Products used for completing household tasks (e.g. snow blower, power tools, lawn mower)

**Generator** - System that produces electricity typically used for remote or backup applications



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