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# **AC 2011-741: A PORTABILITY RUBRIC APPLIED TO THE REDESIGN OF A SOLAR POWER GENERATION SYSTEM**

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# **A Portability Rubric Applied to the Redesign of a Solar Power Generation System**

## **Abstract**

The portability of a system is a crucial design parameter for many products. In particular, for products where mobility is a critical customer need, portability is paramount. This is often the case for example, for products entering into service with the U.S. Military. A concise rubric for measuring a system's portability can be a critical asset when designing or redesigning a mobile system or when comparing two systems where mobility is important. Unfortunately, such a rubric does not exist. The development and implementation of such a rubric is the focus of this research. Note that this rubric could be used across a wide variety of student design projects and, as such, has wide applicability for enhancing engineering design projects. The portability rubric introduced is designed to allow engineers to analyze systems being designed or systems that already exist. In either context, the rubric is used to quantify how portable a system is. The 18 metrics that make up the rubric combine to cover the key components that constitute a system's portability. The rubric is tested using a portable solar array system and a diesel generator set as a comparison datum. The rubric for the power generation systems is a smaller subset of the original 18 metrics that target the key components of power systems. Once the rubric is validated, it is used to re-design a current portable solar photovoltaic power system. Suggestions are made to re-design the system and focus on the areas of concern that were highlighted using the portability rubric, which include weight and size dimensions. As this research was conducted primarily by an undergraduate student, but working in concert with a graduate student and two professors, the educational benefits of such a structure are also enumerated.

## **Introduction**

Portability is defined as the ability to easily be moved or carried<sup>1</sup>. A key component of many military systems is their ability to be quickly assembled/disassembled, moved to different locations, and to use minimum manpower and equipment in order to accomplish the mission. One problem in redesigning systems to increase portability is that there is not currently an established rubric for measuring portability. The portability of a system is a function of several different aspects. We have developed a rubric to measure a system's portability. The rubric includes 18 parameters (Table 1) as discussed in detail below.

In order to use the rubric, each of the 18 portability measures identified above is quantified for the system(s) being evaluated. This information can then be used in two different manners. If the rubric is applied to a number of different systems, then the current state of portability for these systems can be compared. As a second application, the rubric can be used to measure the portability of a current system and to identify opportunities for redesign specifically tailored to increase portability.

In some cases, the list of 18 parameters that constitute the rubric can be shortened as a form of tailoring for a specific application. This is the case when using the rubric for portability analysis of a mobile power generation system. The rubric was shortened to include only the following metrics: weight, largest dimension stowed, volume stowed, largest cross sectional area, and power output per pound weight or power density.

In our current work , the rubric is being used in both of the manners discussed above. First, we apply it to two power generation systems currently being used in military operations; a solar system and a diesel generator. Next, the output from the rubric is used to identify avenues for redesign that will enhance the portability of that system.

#### Background literature review for portability

The topic of portability can be seen as quite broad, encompassing issues such as system weight, dimensions, deployment strategy, and stowage state. The primary function of the system may cause its “portability” to have different nuances. For example, portability of a network access device may emphasize its ability to interface with different types of computer networks. Portability of a space structure would likely emphasize both weight and deploy ability from a stowed (launch) configuration as primary considerations. The context-dependent nature of the definition of portability suggests that a comprehensive literature review in this area could constitute a book in itself. In this light, we have limited our literature review to an overview of books related to portable systems architecture followed by the few references that exist on portable product designs along with some relevant literature on ergonomics and modularity.

There are numerous books which review different aspects of portable systems architecture<sup>10-16,19,21</sup>. The modern embodiments of forms which enhance transportation and relocation of functionality have vastly changed the way we live and interact with the structures around us. The books written on this subject pay special attention to case studies of relevant designs and infer the sociological effects of portability. These books cover many topics ranging from the wearability of designs<sup>12</sup> to the interaction of the organizational structures of roads on our mobility<sup>21</sup>.

Research specific to product design for portability is almost nonexistent. Several studies have, however, been undertaken in relevant topics and on the design of devices which happen to be portable. One such a study examines which regions on the human body are most suitable for portable device attachment during dynamic motion, a topic known as wearability<sup>18</sup>. Another research team developed a collaborative role playing design game for concept generation and enhancement of portability<sup>17</sup>. The article demonstrates the method on design of a communication device. A third research team has undertaken to assess the portability of components during the manufacturing process<sup>20,22</sup>. There are also a number of articles, relating to the design and implementation of inflatable structures<sup>29-37</sup>. A large body of this research is spawned from the science and engineering revolving around the recent development of deployable space structures<sup>29-35</sup>. Such space structures include inflatable antennas, re-entry cushions, domiciles, and satellites. The relevant articles are related to portability in that structures designed for deployment in space must be highly compact and light, which often corresponds to a high degree of portability. These structures must be transported great distances with minimal payload costs. Literature on this topic includes design methodologies for developing structures for portage and deployment to space<sup>29,34</sup> along with analysis of structural requirements for the durability of

inflatable portable structures<sup>30-33</sup>. Other inflatable portable structures have been researched, including the development of inflatable rigidizable wing structures for unmanned aerial vehicles<sup>35</sup> and analysis of the structural properties of a floating aquaculture structure<sup>36</sup>.

Portability as a research topic remains open for investigation. However, ergonomics is conceptually related to portability and has seen significant research advancements<sup>18,23-28,38</sup>. In fact dozens of books have been written on the subject. Research in ergonomics is a useful stepping stone to begin study of portability. The relation between the two fields can be seen in the following way; for a product intended to be portable the ergonomically redesigned version will be more 'comfortable to carry'. A device which is more comfortable to carry is more portable. Research in ergonomic methodology has been included in this literature review below. Significant methods exist for assessing the ergonomic properties of a design both qualitatively and quantitatively. There are also methods for redesign processes to develop a solution which is more ergonomic. The general categories into which ergonomic topics fall are loosely classified as follows:

- Those which model or measure ergonomic behavior:
  - The workplace and workflow<sup>23,24</sup>
  - Stress and fatigue of the user during product use<sup>24-26,38</sup>
- Those which direct new design of ergonomic products:
  - Principles and axioms for developing ergonomic products<sup>23,27,28</sup>
  - Tools and techniques or methodologies<sup>23,24,27</sup>

The methods for ergonomic design reviewed are primarily prescriptive<sup>23,24,26-28</sup>. They tend to be either tabular or questionnaire forms which deduce the ergonomic properties of a product or context. These methodologies are derived from a conceptual flow of the product development process wherein ergonomic design is a distinct process chain from product design, and at intervals the processes can be compared; i.e. design continues for a while then the ergonomic properties of the design are assessed, then the product design is continued for a while and the ergonomic properties are again assessed<sup>23</sup>. There is little methodology for directly incorporating ergonomic consideration in open ended design processes and concept generation.

Additionally research into creating more portable designs can be enhanced by examination of design for modularity. Modular designs can by nature be decomposed. If this process is ergonomically appealing and simple, such designs can be decomposed for transportation. Highly relevant materials includes a book on developing modular designs<sup>16</sup> and a process for conceptualizing modularity as a way of sharing the design space between components<sup>37</sup>.

#### A rubric for portability

Based on the fact that the literature does not have a simple rubric with which to quantify a system's portability, we have developed a set of portability measures that, when taken together,

can be used as a rubric to measure portability. These 18 portability measures are shown below in Table 1.

Table 1: Rubric of 18 Portability Measures

1. Weight or mass
2. Moment of inertia in stowed versus deployed state
3. Position of CG
4. Largest dimension in a stowed state
5. Ratio of largest deployed dimension to largest stowed dimension
6. Volume or compactness in stowed state
7. Ratio of volume in deployed state to volume in stowed state
8. Cross sectional area in stowed state
9. Ratio of Cross sectional area in deployed state to cross sectional area in stowed state
10. Largest diagonal in stowed state
11. Ratio of largest diagonal in deployed state to largest diagonal in stowed state
12. Effort to deploy/stow
13. Energy or work expended to deploy/stow
14. Power needed to deploy/stow
15. Energy density with respect to mass/volume/largest dimension
16. Time to deploy/stow
17. Number of steps to deploy/stow
18. Number of individual components

The development of the 18 portability measures was done by consulting a number of experts in the field of engineering design and requesting that they list what measures they consider to be important factors in determining a system's portability. The input from these experts was first simply combined to form a large set of portability parameters. Then each item on the list was scrutinized to see if it was redundant with other items on the list. The result is the list of 18 portability parameters shown in Table 1.

## Application of the rubric to current power generation systems

Of the 18 portability measures that constitute the portability rubric, 5 were identified as core measures particularly applicable to the mobile power generation systems shown below (Figure 1). After using the reduced, 5 item rubric to analyze the Solar Model R10 portable solar power system and the Quiet Diesel Generator, we found that the diesel generator was significantly more portable. Some of the highlights of this analysis are shown in Table 2. The baseline system for future comparisons after the redesign will be the Quiet Diesel Generator<sup>7</sup>.



Figure 1: Left Solar Model R10, Right Tactical Quiet Diesel Generator Set<sup>7,8</sup>.

Table 2: Highlighting Comparison Between Solar and Diesel Systems<sup>7,8</sup>

	<b>Model</b>	<b>Model</b>	Datum (Diesel Generator)	Normalized Model R10
<b>Metric</b>	Solar Model R10	Diesel Quiet Generator		
Weight(lbs)	5200	911	1	5.7
Largest Dimension Stowed(ft)	22	4.5	1	4.9
Volume stowed(ft <sup>3</sup> )	2141.33	34	1	63.0
Largest Cross Sectional Area(ft <sup>2</sup> )	267.66	13.10	1	20.4
Power Density(KW/lb)*100	0.115	0.549	1	0.21

From this direct comparison, the down sides of using solar power trailers in the field are obvious. Specifically, the weight and size dimensions are much larger, which makes the portability of the system inferior to a diesel generator. The next step is to perform a redesign on the solar power trailer and attempt to optimize the metrics, which are poor in comparison to the competitor of diesel generators. Specific areas for enhancing portability in the redesigned solar system are identified using the 5 critical portability measures. These areas include weight, largest dimension stowed, volume stowed, and cross sectional area. Note that the power density metric has been intentionally left out of the redesign focus criteria because the solar system compares

favorably with the diesel generator in this area. Details are provided below that show that focusing the redesign effort based on these 4 areas has allowed the solar system to make significant progress in its overall portability measurement when compared with the diesel generator.

#### A refined system

In order to increase the portability of the solar system, we investigated a number of options to address the weight and volume issues identified in the previous section. Possible solutions included removing the trailer setup for a lighter pallet setup option. This removed the necessity for heavy axles and wheels which add to the weight of the system. However, the trailer itself obviously provides an aspect of portability. Another proposed change is to alter the framework supporting the solar panels to a lighter material such as aluminum or plastics. In order to reduce the size dimensions it is suggested to make the panels more of a modular assembly rather than being fixed as a single unit to the current frame. The Solar Model R10 is designed to be a “tow into position and turn on” system. In order to make it a smaller size in the stowed state, the panels could fold over one another and collapse into a much smaller area thus reducing the size of the overall system. In addition, if these foldable panels were modular and could be easily removed from the frame, they could be stored in a protected location, separately from the frame, which is likely much more able to withstand the outside weather conditions. This is an important potential improvement as the solar panels are not only the most expensive part of the solar system, but they are by far the least robust in terms of withstanding environmental conditions such a wind, hail, rain and blown debris. The modification of the solar panels to a foldable configuration could also lower the overall weight of the system as the framework could be much smaller. Finally, a modular frame and foldable panels could allow the system to be tailored for the specific power requirements; for example only using a subset of the full solar panel/frame components when a lower level of power is required. This would affect the portability if this reduced power requirement was known before the system’s deployment as the smaller (more portable) configuration could be deployed in contrast to the full system.

As another avenue for using the portability rubric as a redesign tool, we used the rubric to evaluate the commercially available trailer-based solar system called the National Renewable Energy Lab (NREL) Solar Independence Photovoltaic System. We hypothesize that this system will compare more favorably with the diesel generator than the R10 solar system evaluated above. First, we use the portability rubric to evaluate the NREL system in its current form and then we use that assessment information to suggest design changes to make it more portable in comparison to the Quiet Diesel Generator set.

The NREL Solar Independence Photovoltaic System (SIPVS) is a 8kVa, 120/240 Vac/49kWhr Battery Bank/4.56 kW Photovoltaic array. The photovoltaic system consists of 16, 285W solar panels along with 16 lead acid batteries operating at 48 Vdc<sup>2</sup>. The photovoltaic panels are connected to two 4kVa inverters. Each of the 16 panels is stored in the back half of a HighWay Cargo trailer which is split into two compartments, the battery bank/PV storage area, and the inverter room. The 16 panels are connected together using umbilical cords then tied into the trailer through the external connection points located on the exterior of the trailer<sup>9</sup>. Figure 2 shows the system in its deployed configuration.



Figure 2: NREL Solar Independence Photovoltaic System. Storage trailer in background with photovoltaic panel array in upper left of flag demonstration<sup>6</sup>.

### Application of rubric to NREL system

The metrics that were used to analyze the NREL system include: weight, largest dimension stowed, volume stowed, largest cross sectional area and power density(kW/lb). These are the same metrics used to evaluate the systems in the previous sections. Evaluation data is shown in Table 3.

Table 3: Analysis of NREL Trailer System<sup>9</sup>

	<b>Model</b>	<b>Datum (Diesel Generator)</b>	<b>Normalized NREL System</b>
<b>Metric</b>	NREL SIPVS		
Weight(lbs)	6500	1	7.1
Largest Dimension Stowed(ft)	12.5	1	2.8
Volume stowed(ft <sup>3</sup> )	600	1	17.6
Largest Cross Sectional Area(ft <sup>2</sup> )	48.0	1	3.7
Power Density(KW/lb)*100	0.123	1	0.22

From the rubric it was found that the major concerns for the NREL system revolved around the weight and overall size dimensions (volume). These were the same primary considerations as for

the R10 Solar systems initially analyzed (Table 2). Note however, from the data in Tables 2 and 3, that the NREL system is considerably more portable than the R10 system. For the NREL system, in addition to the weight and size during the setup process, other areas of concern were found to include, a long set up time, need for minimum of two people to set up the array, and awkward mounting stands for the solar panels. Using this information the next step was to propose re-design alternatives for the system to address these issues.

Figure 3 shows two different styles of solar panels that are commercially available currently. The panel on the left is a cloth lined foldable panel and the panel on the right is a plastic roll-able panel. These designs although not as efficient as a hard backed solar panel, (~8% for the roll-able and foldable vs. ~17% for the hard backed) are significantly lighter and easier to maneuver. Table 4 highlights the comparison of a foldable solar panel, a roll-able solar panel, both commercially produced by Powerfilm Inc.<sup>5,6</sup>, and a traditional hard backed panel produced by DMSolar, which will be the datum for the comparison<sup>3,4</sup>. In order for the comparisons to be equal across all three panels the total power output is set to 60 watts. The foldable option produces 60 watts and the traditional hard backed panel also produces 60 watts. The roll-able panel produces 28 watts therefore two panels connected in series are used for this comparison to give relevant data.



Figure 3: Possible Solar Panel Options, left F15-3600 60 Watt foldable solar panel, right R28 28 Watt roll-able solar panel, below DMSolar 60 Watt solar panel<sup>3-6</sup>.

Table 4: Highlighting Comparisons of Solution Options for Solar Panels<sup>4-6</sup>

Metric	Model				Datum	Reference
	F15-3600 (foldable)	F15 -3600 Normalized	R28 (roll-able)	R28 Normalized	DM Solar 60W	DM Solar 60W
Weight(lbs)	3.19	0.21	3.6	0.23	1	15.4
Largest Dimension Stowed(ft)	0.92	0.36	1.50	0.59	1	2.55
Volume stowed(ft <sup>3</sup> )	0.12	0.13	0.25	0.27	1	0.928
Largest Cross Sectional Area(ft <sup>2</sup> )	17.6	3.11	18.05	3.19	1	5.66
Power Density(kW/lb)*100	1.88	4.82	1.55	3.85	1	0.39

Table 4 shows that the foldable and roll-able solar options are better in all the size parameters except largest cross sectional area and are significantly better in power density and weight. The datum solar panel is a hard plastic backed solar panel that produces the same power as the F15-3600 foldable solar panel, 60 watts<sup>4</sup>. Based on this if the portability requirement was for lighter weight or smaller stowed dimensions, the foldable and roll-able options are much better choices. If the portability requirement is for smaller deployed size, then the traditional panels are the better choice.

Potential re-design of the panel support system

The current NREL system has many design flaws to include: the mounting stands are bulky and contain too many components, the size of the solar panels is too big, stand setup takes too long, and the weight of the system is also too big.

One re-design option has integrated the stand into the solar panel modules themselves rather than having individual components. By adding them to the panels the setup time will be reduced. See figure 4 below for preliminary design next to current design. The legs are then attached to each panel allowing ease of setup and the integrated stakes also eliminate excess components.

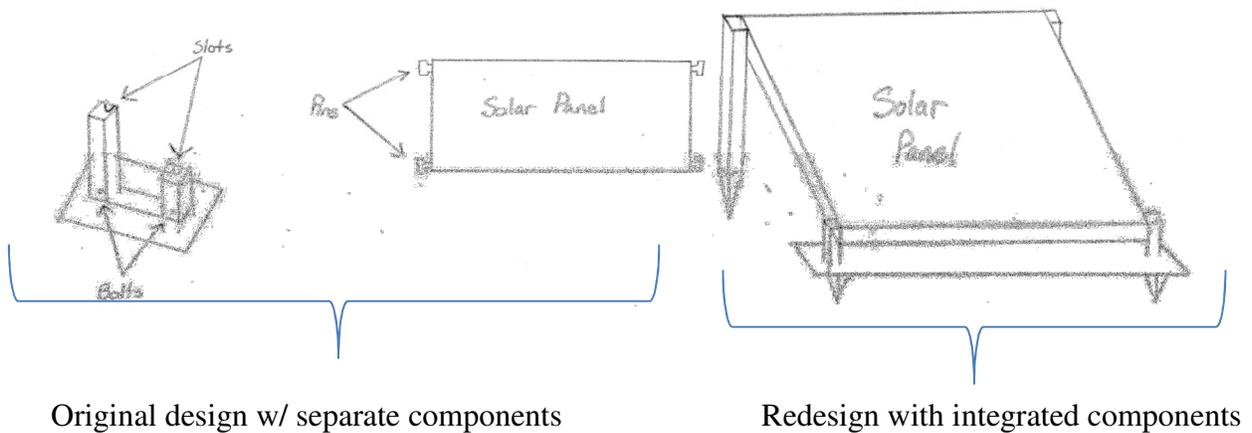


Figure 4: Preliminary Re-design side by side to current design.

Instead of re-designing the mounting system, another option is to simply replace the hard backed solar panels with either the foldable panels or roll-able panels. The analysis performed earlier shows that these solar panels are much more portable in terms of weight and deployed dimensions and therefore may be a better option for such an application.

Potential re-design of the panel type

Table 5 compares the use of the three different solar panel options (foldable, roll-able and hard backed) for potential use on the NREL system. This table shows the dimensions required for the different types of solar panels and the final weight and power density if a single large foldable/roll-able panel is used to replace the 16 individual panels. The NREL system provides the 8kVa power output through 4.56 kW of solar panel power. The additional power comes from the battery bank attached to the system. For this comparison only the output from the solar panels is considered; each type of panel producing roughly 4.56kW.

Table 5: Highlighting New Solar Panel Options 4.56kW Outputs

	<b>Model</b>		Current NREL panels
<b>Metric</b>	Foldable	Roll-able	Hardbacked
Weight(lbs)	242	293	1280
Largest Dimension Stowed(ft)	10	20	8
Volume stowed(ft <sup>3</sup> )	800	1570	240
Largest Cross Sectional Area(ft <sup>2</sup> )	1300	1300	768
Power Density(KW/lb)*100	1.88	1.56	0.356

Table 5 shows foldable and roll-able options that are sized to produce the same power as the current hard backed panels employed on the NREL system. Note that the foldable and roll-able solar panel options would take up a larger area when deployed and take up a larger volume when completely stowed. The stowed roll-able option takes up twice that of the foldable because the stiff plastic backing can only bend so far before causing damage to the solar panel attached to it. In addition, there is wasted volume due to the hole through the middle of the roll. The volume of the roll-able is roughly 8 times that of the hard backed panels again because of the restriction imposed by the plastic backing and how the solar panels are attached to that plastic. The foldable option also has a large volume when stowed due to the compressibility of the panels as they are folded. They can only be folded down so far without damaging the panels. The cross sectional area of the fold-able and roll-able options are twice that of the hard backed panels due to the difference in efficiency of the panels. The hard backed panels are twice as efficient as its flexible counterparts, 8% for the flexible options and 17% for the hard backed panels. The flexible panels need to be roughly twice as large to produce the same amount of power output due to this difference in efficiency. However, the weight of both flexible options is over four times lighter than the hard backed panel options. The lighter weight makes it easier to maneuver the system into position for deployment, therefore more portable in that aspect. The metric shows

that the three types of panels each have their advantages and disadvantages. Depending on the portability needs, a decision can be made to meet those needs.

Currently in the field, deployed locations, there are little restrictions on the size a base can occupy. This means that the larger panel options are feasible as replacements for the NREL system. If the portability need is for lighter weight panels then the foldable and roll-able options are significantly better choices. However, if the need is for smaller size when stowed and when deployed then the traditional panels are the correct choice.

Another component of the system that needs to be addressed are the charge controllers and inverters that take in the power from the solar array and direct it either the battery bank for storage or out the power outlet units. Most of the technology for these systems hasn't changed significantly since when the NREL system was produced. New systems are slightly smaller and only slightly lighter. Other aspects of the system that have changed significantly in the past few years are the primary focus of the redesign as they will contribute more to the portability of the system.

Currently the heaviest component of the system is the battery bank. Each battery weighs roughly 80 pounds. With 16 batteries this adds almost 1300 pounds to the overall system making this an area of concern for portability. Currently engineers are working to design lithium ion batteries that are compatible with solar cells. Lithium ion batteries are significantly lighter than lead acid batteries and typically are much smaller in size. Another option is to not use a battery bank, and instead grid tie a diesel generator into the system to provide power at night and during times when the solar array does not provide enough power to the grid. As shown above, the diesel generators are already very portable on their own and grid tying one into the NREL system can easily be achieved.

#### Educational use of the portability rubric

Portability is a growing concern in many areas of engineering. Even systems that are designed to remain in place for years can have an aspect of portability. This is because these systems have to arrive on location whether it is in components or a complete system. Analyzing the portability of the system would allow the manufacturer to save time and money on transportation. In this case, analysis of portability of a system encourages a student design team to engage with full life cycle design considerations.

In a senior Capstone design team, portability is often a concern. By using the rubric they can quickly analyze the system and find subsystems or components that are more important to the portability of their design and focus their design/redesign on those subsystems or components. Usually teams are tasked with taking an existing idea and making it more effective, more efficient, or of better quality. Teams can now take this portability study and apply it to their projects, to further enhance their system. This portability rubric optimizes their time and by allowing the team to quickly analyze where their system lies in terms of portability. A decision can then be made on whether enhancing portability would significantly improve customer satisfaction; and therefore whether the design effort should include focus on portability.

Educational benefits for undergraduate engineering students as exemplified by this research

The process followed to arrive at the research results in this paper is itself an educational enhancement that could be adopted by others. The process involved encouraging an undergraduate to identify a “research-oriented slice” of the overall capstone design problem; in this case the issue of measuring and enhancing portability. This portability study has shown how the research process begins and how it develops into a final deliverable. Working with several experts in the field and also graduate level students at the University of Texas has allowed the undergrad to see what it is like to perform graduate level research. Disseminating the research by writing a paper intended for publication and presentation in front of a national audience has been a good experience and provides a taste of what the next level of education involves. As a “soon-to-be” officer in the United States Air Force, this research and the resulting publication will provide a strong “performance evaluation bullet” point that reflects the undergrad’s ability to communicate well and willingness to work hard. Finally, working with experts in the field provides opportunities for future research as well as individuals that can write grad school application references based on the undergrad’s ability to do self-initiated research.

## Conclusion

Portability is an important aspect that needs to be addressed when designing new systems intended to be mobile. This is extremely important with the United States Military as they are highly mobile and deploy to locations all over the globe. In order to perform their mission they must bring their own equipment making portability a critical issue.

The analysis technique created through this research was the development of a portability rubric. This rubric contains a total of 18 individual metrics used to rate a system on how portable it is. The rubric is meant to be used to analyze systems in the design process and find areas that reduce the portability of a system based on the requirements of a system. These areas can then be focused on and portability of the overall system can be increased. The rubric can also be used to analyze systems already in use to develop a strategy of how to re-design certain components and increase the portability aspect of that system.

As an example, the rubric was used on the design of portable power units including solar power arrays, and diesel generator sets. The focus was to see if solar arrays could be used in place of diesel generators in a deployed environment to provide power to the soldier. Currently issues with generators include the ability to obtain fuel to run them and maintenance issues in obtaining parts. Solar power arrays require no fuel to operate and are therefore being considered as a possible option to replace generators. Using the rubric developed specifically for these types of systems it was found that solar arrays have draw backs in portability with weight and size dimensions when compared to a diesel generator. Using the rubric and metrics it was easy to find the weaknesses of solar arrays and allowed for the focus of re-designs to concentrate on those areas of concern. The portability rubric made the process of narrowing down the pitfalls of solar arrays much easier and gave quantitative results to compare between the systems. Finally, some different types of solar panels were evaluates using the portability rubric. In particular, consideration was given to replacing the hard backed panels on an NREL solar system with either foldable or roll-able panels. It was determined that the roll-able or foldable options would in fact drastically improve the portability from a weight standpoint, but that both the stowed and

deployed dimensions of the system would be increased if these options (foldable or roll-able) were employed.

In conclusion, the portability rubric developed as part of this research provides an analysis capability which has not been available before. Future capstone teams to optimize their time and allow them to focus their attention on more important aspects of their systems can use this rubric. Specifically, systems can be quantitatively evaluated in terms of their portability and design decisions can be made in light of this data.

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