Providing photons for food in regenerative life support: A comparative analysis of solar fiber optic and electric light systems

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Providing photons for food in regenerative life support: A comparative analysis of solar fiber optic and electric light systems

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Direct use of sunlight in greenhouses is common on Earth, but planets without atmospheres do not filter meteorites and cosmic radiation, making direct use of sunlight very difficult. Indirect approaches are necessary. Photosynthesis for food production requires two orders of magnitude more light than is needed for optimal human activity and this requirement is thus a significant component of total system cost. The most cost effective solution is either a system that focuses photons using concentrating mirrors then transmits the photons using fiber optic cables, or a system that uses photovoltaics (PV) and LEDs to generate electricity and convert it to photosynthetic light. A previous analysis in 2008 found that a solar fiber optic system had a lower equivalent system mass (ESM) than a system using PV and electric lighting, but advances in technology since 2008 warrant a reevaluation of these approaches. Here we analyze the ESM of these technologies for both Lunar and Martian bases. Although both systems have improved over the past decade, PV and LED technologies have experienced greater advances and the ESM of the options is now similar. A sensitivity analysis indicates that improvements in the LED electric lighting efficiency have been the most significant factor in the reduced ESM. Qualitative parameters important to system design are discussed for each mission. Although the focus of this work is photosynthetic lighting, our analysis can be applied to multi-purpose lighting in a spacecraft or habitat.

Nomenclature

C	=	cooling requirement
C_{eq}	=	mass equivalency factor for cooling
CT_{eq}	=	mass equivalency factor for the crew time
$CT \cdot D$	=	crew time requirement in hours
ESM	=	equivalent system mass
IR	=	infrared
LED	=	light emitting diode
M	=	physical mass
M_C	=	mass to cool
M_L	=	mass for lighting
P	=	power requirement
P_{eq}	=	mass equivalency factor for power generation
$P_{eq,collection}$	=	collection mass equivalency

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$P_{eq,emission}$	=	emission mass equivalency
$P_{eq,transmission}$	=	transmission mass equivalency
PAR	=	photosynthetically active radiation
PMAD	=	power management and distribution
PPFD	=	photosynthetic photon flux density
PV	=	photo voltaics
SFO	=	solar fiber optic
SPD	=	spectral photon distribution
V_{eq}	=	mass equivalency factor for pressurized volume

I. Introduction

THE use of direct sunlight to provide photosynthetically active radiation (PAR) to plants via solar fiber optics (SFO) has been studied for over two decades (Drysdale and Sager 1996). Twenty years ago, converting sunlight to electricity and electricity to PAR was less than 5% efficient and the best SFO systems to provide PAR were 40% efficient. The superior performance of SFO held promise of saving mass, power, and cooling expenses over electric lighting.

More recently, Drysdale et al. (2008) estimated that SFO still exceeded the performance of electric lighting by a factor of three. This analysis assumed photovoltaics and lighting efficiencies as 20% each, resulting in a 4% system efficiency. PV efficiencies are now 35% (Beauchamp et al. 2017). The current energy efficiencies of blue, white, and red LEDs are 93%, 76%, and 81% respectively (drive current 100 mA per mm^2, junction temperature 25° C; Kusuma et al. 2020). The combined system efficiency has improved seven-fold since Drysdale et al. (2008). During the same time, estimates indicate that the transmission efficiency of an SFO system has increased from 40 to 65% (Nakamura et al. 2015). Although both SFO and PV/LED technologies have advanced in the last decade, solar photovoltaics and electric lighting from LEDs have had greater improvement. We conducted an ESM analysis using the most current technologies for both systems.

We also estimated the mass requirements of future iterations of both systems. In 5 years, SFO, PV, and ensemble LED efficiencies are expected to reach 76%, 38%, and 88% respectively (Nakamura 2009, Beauchamp et al. 2017, Kusuma et al. 2020). Since Lunar and Martian outposts are unlikely to be established within 5 years, the future efficiency estimates are likely more indicative of flight hardware performance.

In the SFO system, light may be concentrated by either mirrors or Fresnel lenses. In 2002, Jack et al. found that parabolic mirrors were 75% more efficient than lenses, so subsequent SFO research has thus utilized mirrors. After being reflected by the mirrors, the solar radiation is filtered before being focused into the optical cable. In larger SFO lighting systems, a centralized group of concentrating mirrors can supply photons to an array of growth chambers spread radially from the mirrors (Furfaro et al. 2014; Zeidler et al. 2017). In smaller systems, the mirrors are envisioned to be mounted directly on top of the chambers, despite this being valuable real estate for radiators (Hanford and Ewert 1996).

The electric system includes PV, a power management and distribution (PMAD) system, and LED fixtures. LED technology has now been widely studied and the photon output is highly efficient for photosynthesis (Massa et al. 2007; Kusuma et al. 2020).

Figure 1 shows a conceptual diagram of these two systems.

The SFO system can be coupled with a PV system that is powered by photons beyond 700 nm. The resulting electricity is then used to power electric lights. We refer to this system as the Hybrid system in this analysis.

The analysis was scaled to provide photosynthetic photon flux density (PPFD) of 1000 µmol m^{-2} s^{-1} to an internal plant growth area. Since there are no significant capital costs incurred with any system, the mass scales linearly with PPFD and the analysis is valid regardless of the flux of photons. We have conducted a sensitivity analysis and verified that the relationship between PPFD and ESM is linear for all systems. This means that the ESM ratio of the systems is independent of PPFD.

The total system efficiency is not an important factor when considering heat loads because heat generated through external inefficiencies are assumed to be passively cooled. However, the internal efficiency influences the amount of heat generated in the chamber, which is expensive to remove (Anderson et al. 2018). This value is not equal between systems and is thus an important consideration in the trade study.

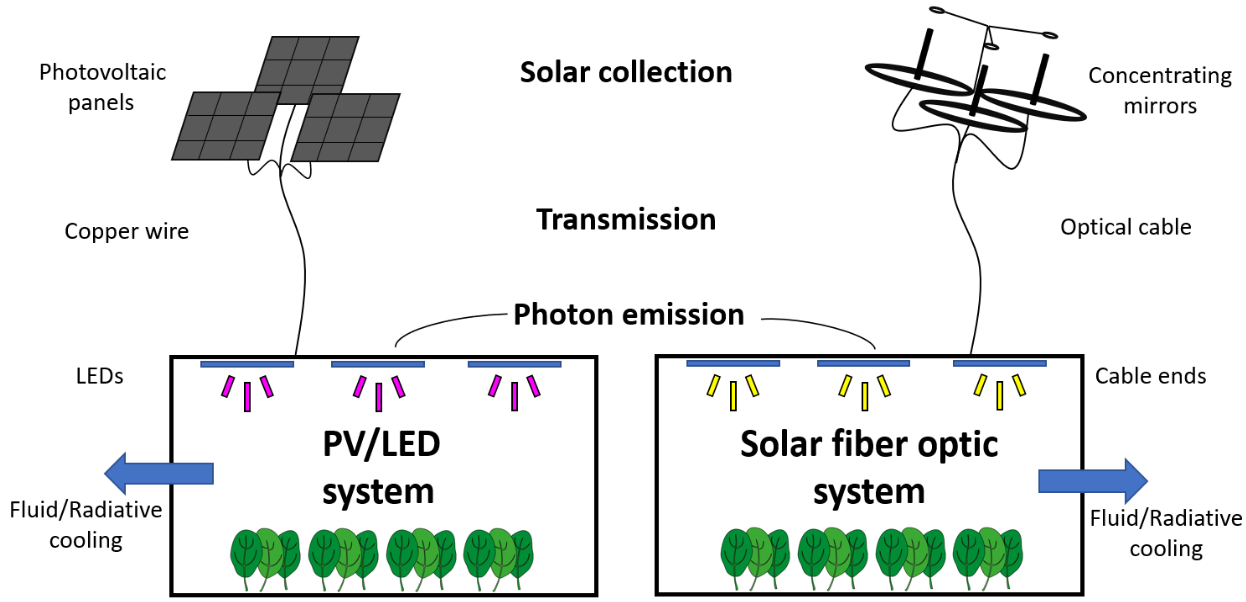

Figure 1. Schematic diagram of the PV/LED and SFO systems showing collection, transmission, emission, and cooling components for both systems.

One important advantage of LEDs is that the spectrum can be adjusted to achieve a lower energy flux for the same photon flux. This change in energy flux for a given spectral photon distribution (SPD) is calculated using Planck's equation ($E = hc / \lambda$). Two extremes can be demonstrated with photons at 400 and 660 nm. For the same photon flux density, photons at 400 nm would result in a 65% higher energy flux than red photons at 660 nm. Red photons at 660 nm are efficiently produced by LEDs (Kusuma et al. 2020) and are 30% more efficient for photosynthesis than blue photons (McCree 1971). These LEDs, therefore, comprise the majority of the LED spectra. We assume a SPD that provides 95% of the flux from red LEDs and 5% from blue LEDs. This spectrum is compared to solar in Figure 2.

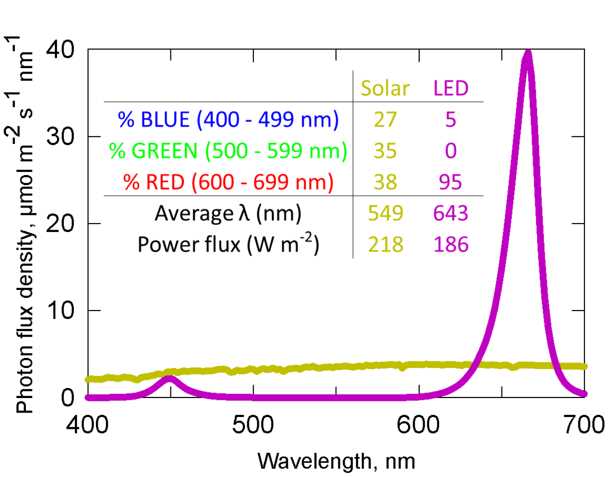

Figure 2. Comparison of solar (SFO) and LED (electric) spectra. SFO spectrum is mostly fixed, while the LED spectrum can easily be manipulated. Notice the difference in power flux between the two spectra due to the longer wavelength photons of the electric system.

We assume that the emission efficiency of SFO is unity; the only energy introduced inside the chamber from the optical fibers is the photons. No additional heat is introduced. In addition to delivering photons, the electric system generates heat due to transmission and emission inefficiencies in the LEDs and PMAD. This heat adds to the load generated by the photons. The internal heat generated from the hybrid system depends on the ratio of PAR to IR content in the incident radiation. Regardless of this ratio, the hybrid internal heat load is between the pure SFO and electric systems.

II. Modelling approach

Two major costs associated with lighting are cooling and mass of the light delivery system, including energy collection, transmission, and emission. These properties possess unique dimensions, so it is beneficial to homogenize them to facilitate the trade study. To accomplish this, this study employs the Equivalent System Mass model outlined by Levri et al. (2003). This process equates system requirements to a single mass term since project costs are dominated by launch costs.

The equation for ESM is given as

$$ESM = M + V \cdot V_{eq} + P \cdot P_{eq} + C \cdot C_{eq} + CT \cdot D \cdot CT_{eq}. \quad (1)$$

In relation to a system, M is its physical mass, V is its volume, V_{eq} is the mass equivalency factor for pressurized volume, P is its power requirement, P_{eq} is the mass equivalency factor for power generation, C is its cooling requirement, C_{eq} is the mass equivalency factor for cooling, $CT \cdot D$ is its crew time requirement in hours, and CT_{eq} is the mass equivalency factor for the crew time.

Calculating the ESM for the entire plant growth system requires consideration of many additional parameters, including water, pumps, trays for plants, and crew time for maintenance, but since we are only comparing lighting systems, we simplify this equation by assuming the plant growth facilities are equal in mass and require equivalent amounts of crew time to maintain. Furthermore, the pressurized volume occupied by the internal fibers/lighting system is also assumed to be equal. The mass, volume, and crew time aspects of ESM can thus be ignored.

This reduces the ESM considerations to:

$$ESM = P \cdot P_{eq} + C \cdot C_{eq}. \quad (2)$$

The ESM of each lighting system is comprised of a mass to provide photons

$$M_L = P \cdot P_{eq} \quad (3)$$

and a mass to cool

$$M_C = C \cdot C_{eq}. \quad (4)$$

These expressions are combined to obtain the general form

$$ESM = M_L + M_C. \quad (5)$$

The cooling mass (M_c) follows the same form in all systems; the cooling equivalency (C_{eq}) is constant, while the rejected heat (C) varies. On the other hand, the lighting mass (M_L) must be tailored to fit each lighting system. As discussed in Section I, the power requirement P between electric and SFO systems are unique and dependent on the emission spectra. The power equivalencies, P_{eq}, are also unique, but may be expressed in a common form as

$$P_{eq} = P_{eq,colleciton} + P_{eq,transmission} + P_{eq,emission}. \quad (6)$$

The collection equivalency, $P_{eq,colleciton}$, refers to the PV or solar concentrating mirrors, the transmission equivalency, $P_{eq,transmission}$, refers to the electric or fiber optic cable, and the emission equivalency, $P_{eq,emission}$, refers to the LED assembly. The emission via SFO requires no hardware beyond the cable. The hybrid system equivalencies include aspects from both electric and SFO systems.

A. Assumptions of efficiencies and mass equivalencies

The ESM of each lighting system is calculated for Lunar and Martian bases. The boundary conditions presented by a location dictate nearly all facets of ESM (Anderson et al. 2018). The sunlight availability at a location influences the power equivalency and the concentrator/cable mass.

Sunlight availability on the Moon assumes the solar constant (1.36 kW per m^2), which is the maximum intensity on the Moon. This analysis assumes a polar location where the maximum intensity is always available.
Sunlight on Mars assumes the maximum distance from the Sun and 30% transmission loss from atmospheric dust, resulting in 0.35 kW per m^2 available radiation. Mars has a variable radiation environment. Its orbit is more elliptic with variable transmission loss. On Mars, a lower light intensity is assumed to ensure nominal operation throughout the year.

Table 1 shows efficiencies, power mass equivalencies, and cooling mass equivalencies. SFO collection mass equivalencies assume a concentrator density of 3.57 kg per m^2 and transmission efficiencies of 65% for current technology (Nakamura et al. 2015) and 76% for near term (Nakamura 2009). This increase in efficiency for near term is based on increases in the primary mirror reflectivity, intercept factor, and cable transmission efficiency.

SFO transmission mass equivalency assumes a numerical aperture of 0.53, fiber diameter of 2.2 mm, and a fiber density of 9.94 g per m (CeramOptec; https://www.ceramoptec.com/en/industrial-products/fibers.html). The mass equivalencies can be calculated from these values using the equations provided by Nakamura et al. (2015). We calculate the Martian solar half angle at perihelion. Other equivalencies and efficiencies are described at the bottom of the table.

Coincidentally, the cooling equivalencies on the Moon and Mars are nearly equal. The equivalencies at each location were estimated in a similar manner followed by Hanford and Ewert (1996). These estimates are made assuming the utilization of lightweight radiators and heat pumps. The cooling equivalency was included in the sensitivity study to ensure the trade study is largely unaffected by this assumption.

Unlike cooling mass, the lighting mass depends on the location. The contributions of lighting and cooling masses to ESM are outlined in the baseline case analysis.

Table 1. Assumption of efficiencies and mass equivalencies for ESM analysis of solar fiber optic (SFO) and LED electric lighting systems for plants.

	Current Technology				Near Term (5 years)			
	Moon		Mars		Moon		Mars	
	Electric	SFO	Electric	SFO	Electric	SFO	Electric	SFO
Power into chamber (W)*	186	218	186	218	186	218	186	218
Light emission efficiency	0.84(1)	1	0.84	1	0.88(1)	1	0.88	1
Power requirement (W)	221	218	221	218	211	218	211	218
Collection (kg per kW)	10(2)	10.1(3)	39.6(5)	40.8(3)	5(2)	8.9(3)	19.8(5)	35.1(3)
Transmission (kg per kW)	1	6.8(3,4)	1	14.3(3,4)	1	5.9(3,4)	1	12.3(3,4)
Emission (kg per kW)	2	0	2	0	2	0	2	0
Total P_{eq} (kg per kW)	13	16.9	42.6	55	8	14.7	22.8	47.4
External C_{eq} (kg per kW)	51.9(6)	51.9	52.0(6)	52.0	51.9	51.9	52.0	52.0
Internal C_{eq} (kg per kW)	25(7)	25	25	25	25	25	25	25
Total C_{eq} (kg per kW)	76.9	76.9	77	77	76.9	76.9	77	77

*Assumes a photosynthetic photon flux density (PPFD) of 1000 µmol m^{-2} s^{-1}, see Fig. 3

(1) estimated from Kusuma et al. 2020; (2) Beauchamp et al. 2017; (3) Takashi Nakamura, personal communication; (4) CeramOptec Website (5) estimated from Beauchamp et al. 2017; (6) estimated from Hanford and Ewert 1996 [assumes lightweight radiators and heat pumps]; (7) Anderson et al. 2018

III. Results

The ESM for each system is calculated by inserting the assumptions in Table 1 into the equations in Section II. A summary of the results of this process is included in Table 2.

Table 2. Calculation of ESM for both systems on the Moon and Mars for current and near term conditions for solar fiber optic (SFO) and LED electric lighting systems for plants. Power requirement, P_{eq}, and C_{eq} are from Table 1.

	Current Technology				Near Term (5 years)			
	Moon		Mars		Moon		Mars	
	Electric	SFO	Electric	SFO	Electric	SFO	Electric	SFO
Power requirement (kW)	0.221	0.218	0.221	0.218	0.211	0.218	0.211	0.218
Total P_{eq} (kg per kW)	13	16.9	42.6	55	8	14.7	22.8	47.4
M_L (kg)	2.9	3.7	9.4	12.0	1.7	3.2	4.8	10.3
Total C_{eq}(kg per kW)	76.9	76.9	77	77	76.9	76.9	77	77
M_C (kg)	17.0	16.8	17.0	16.8	16.2	16.8	16.2	16.8
ESM (kg)	19.9	20.4	26.4	28.8	17.9	20.0	21.1	27.1
Ratio of Electric/SFO ESM	0.97		0.92		0.90		0.78	

The ESM for the SFO and electric systems is included for each scenario analyzed. The ratio of the electric to SFO system mass is included at the bottom and indicates that the electric system is lighter at all locations. Moreover, the ratio decreases with technology advancements, suggesting that future technological advancements favor the electric system. The hybrid system has been omitted from Table 2 because its ESM is between those of the electric and SFO systems.

The near term ESM for each system on Mars is included in a diagram in Figure 3 to show an example of this calculation.

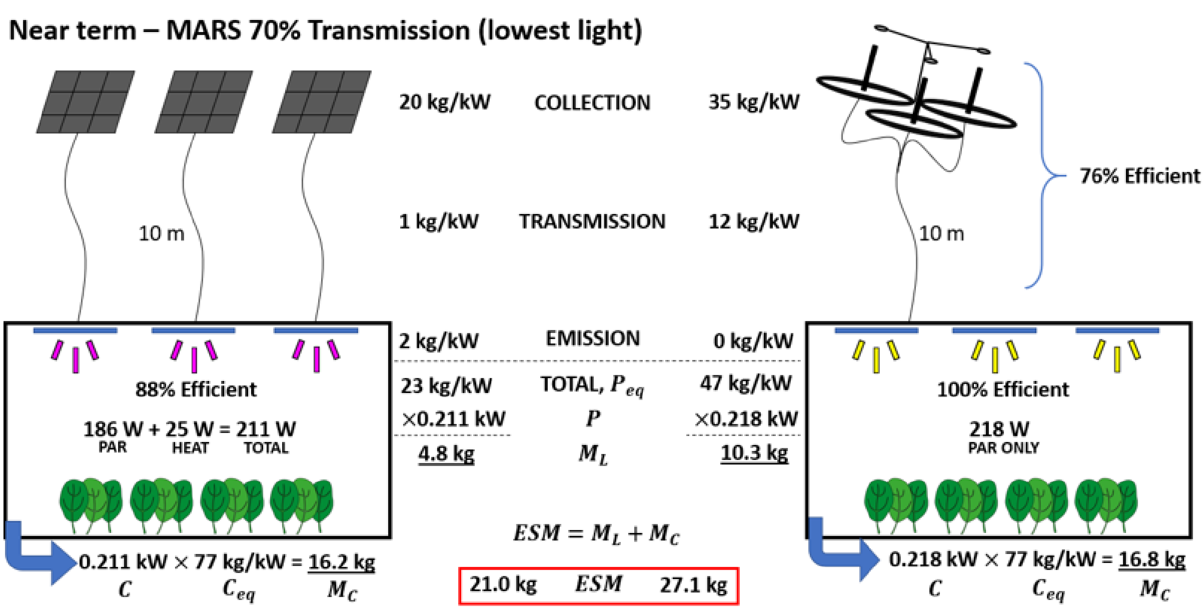

Figure 3. Example ESM comparison of the two technologies for a near term (5 years) Mars base.

A. ESM Analysis

Electric, SFO, and Hybrid lighting systems were implemented in Lunar and Martian ESM models. Using the assumptions listed in Table 1, the ESM for the lighting and cooling of each system are shown in Figure 4 for the Moon and Mars.

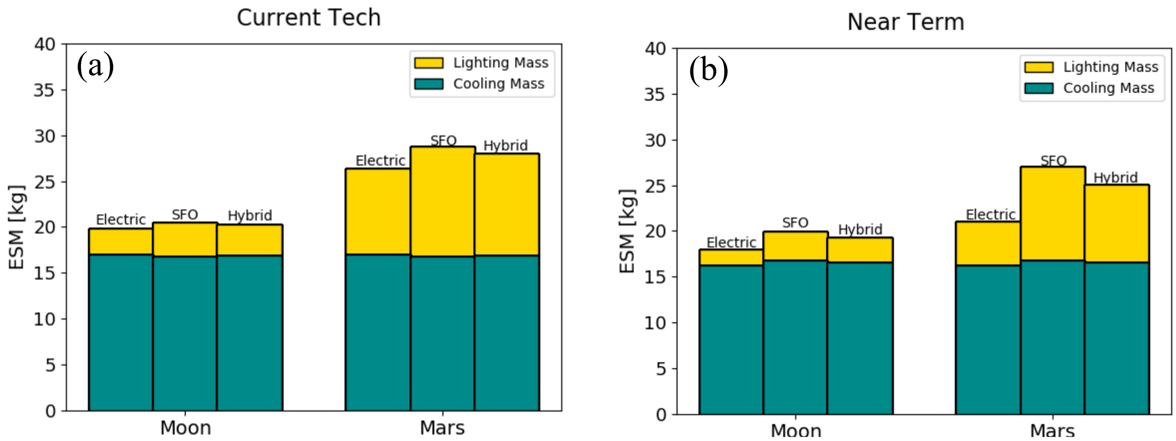

Figure 4. ESM comparison for current and near term (5 years) lighting systems on the Moon and Mars.

The differences among systems on the Moon are small. The ESM ratio of Electric to SFO is 0.9, which is significantly lower than 3.25 found by Drysdale et al. (2008). The hybrid system is mid-tier in all ESM facets: total mass, lighting mass, and cooling mass.

For the Martian base, the electric system has the lowest ESM, followed by the hybrid then SFO systems. The ratio of electric to SFO ESM on Mars is 0.78. Like the Lunar base, this ratio is much lower than found by Drysdale et al. (2008). This is because the technological advancements in the past decade have favored electric over SFO lighting systems. Potential benefits of further advancements are discussed in the sensitivity analysis.

B. Sensitivity analysis

A sensitivity study was performed to analyze the sensitivity of ESM to assumptions. All near term assumptions are based on projected technological performance in 5 years, so there is inherent error in estimating future technological capabilities. The key assumptions affecting ESM are the solar intensity, LED efficiency, SFO efficiency, fiber cable length, PV power equivalency, cooling equivalency, and photon output.

The cooling, lighting, and total equivalent system masses as a function of available sunlight are shown in Figure 5. The cooling mass is nearly constant since modelling has been normalized to a PPFD of 1000 μmol m^{-2} s^{-1}, and the internal thermal load and cooling equivalencies are approximately equal on the Moon and Mars. Unlike the cooling mass, the power mass is sensitive to solar availability – particularly in lower quantities. The ESM differences in low light regimes are dominated by the lighting mass. The electric system is more mass-efficient at providing light, so it is the superior system in the lower lighting conditions at Mars.

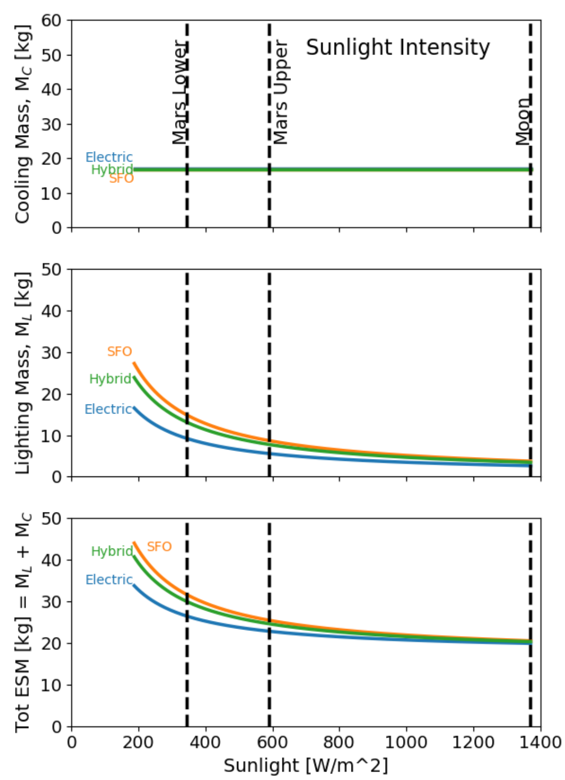

Figure 5. Mars Lower: 30% transmission loss at aphelion, Upper: 0% transmission loss at perihelion

Besides solar availability, the ESM response to changing other assumptions is unique to each location. To distinguish these differences, a separate sensitivity analysis is performed for the Moon and Mars. The Lunar analysis is included in Figure 6.

LED efficiency is the most significant variable in determining ESM for electric systems on the Moon (Figure 6a). This is the only variable that influences both the lighting and cooling mass of the electric system. At lower efficiencies, more power is needed to generate useful photons, and the excess power - which is inversely proportional to the efficiency - must be rejected as heat. Lighting efficiency has increased four-fold since Drysdale et al. in 2008. With this improvement, the cost for lighting and cooling each drop by a factor of four.

Unlike electric efficiency, an increase in SFO efficiency decreases the lighting mass but not the cooling mass. On the Moon, the lighting mass is small compared to the cooling mass. Any percentage decrease of an already-small mass does little to change the overall system mass (Figure 6b).

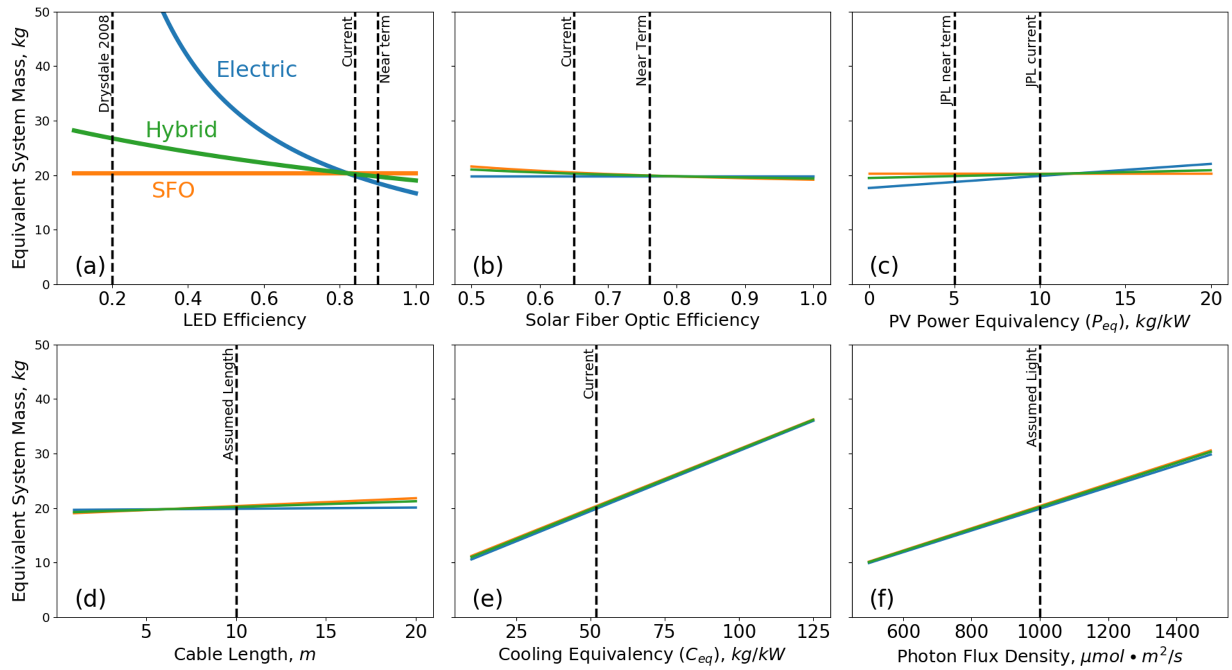

Figure 6. Analysis of ESM on the Moon. Advances in LED technology have dramatically decreased the ESM for electric lighting (6a).

The same applies to the P_{eq} of PV. The lighting mass is small compared to the cooling mass for the electric system, so the ESM is not highly sensitive to this power equivalency (Figure 6c).

System mass increases with increasing desired PPFD. This difference increases at a fixed rate, so the ESM ratio remains constant among systems. This indicates that this analysis can identify a superior lighting system for any desired photon intensity.

A similar sensitivity analysis is performed for Mars in Figure 7.

As in the case with the Moon, the LED efficiency is the most significant factor affecting the ESM of electric lighting on Mars (Figure 7a). With present-day LED technology, the electric system is superior to the near term SFO system. This suggests that even with improvements made to the SFO system, the electric system will be preferred.

Generally, the ESM for each system is more sensitive to the altered parameters on Mars than the Moon. This is because on the Moon, ESM is largely dictated by M_C (see Figure 4). On Mars, M_C is nearly the same as on the Moon, but as light intensity decreases, M_L increases. Since M_L is more relevant on Mars, it is expected that the ESM will be more sensitive to light-related masses. Observe the differences between Figure 6b-d and Figure 7b-d. In the Figure 6 subplots, no system is particularly sensitive to the assumptions. Meanwhile, the counterpart subplots in Figure 7 show higher sensitivity to the lighting assumptions.

As on the Moon, the ratio of ESM between systems on Mars is independent of light provided. This suggests that the system with the lowest ESM at a location will remain superior regardless of scale of implementation.

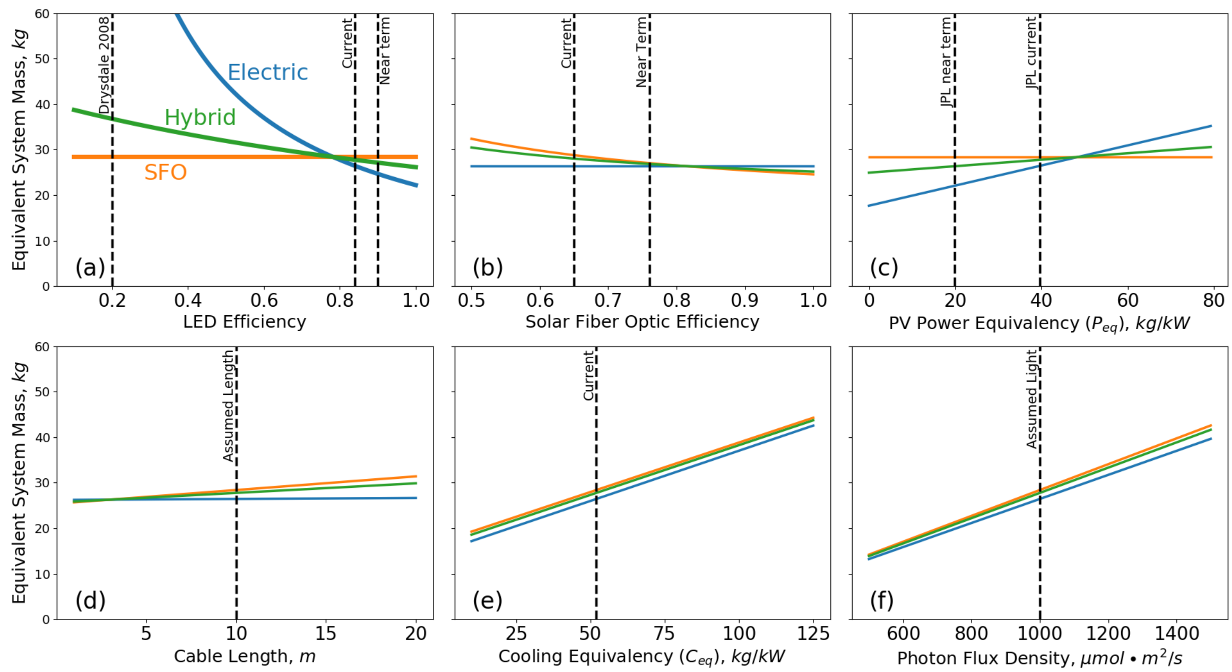

Figure 7. ESM sensitivity for Mars. Advances in LED technology have dramatically decreased the ESM for electric lighting (7a). Advances in photovoltaics also decrease the ESM of an electric system (7c).

IV. Discussion and Conclusions

The PV/LED (electric) system has a lower ESM for both locations and both time horizons. Since the analysis of Drysdale et al. in 2008, the PV/LED photon delivery system has caught up and passed the SFO system. An increase in LED efficiency over the past 20 years decreases system mass in two ways. First, it reduces the amount of electricity required to be produced by the PV, thus decreasing the lighting mass. Second, higher efficiencies result in less heat, lowering the cooling mass.

Except for LED efficiency, the ESM comparison is minimally sensitive to assumptions. Even considering the potential future improvements in technology for a SFO system, PV/LED systems still have lower ESM.

The operational flexibility of each system is a critical consideration that has not been included in our analysis. We assumed that light would be continuously available on the Moon, but this is only possible at polar locations. Even if light is always available, plants benefit from approximately 8 hours of darkness each 24-hour period. During this time, the SFO would have to be disengaged, but the electricity from the PV/LED system could be used for other purposes. This is a large advantage for electric systems that cannot easily be included in the ESM comparison.

Any non-polar point on the Moon is typically exposed to 2 weeks of daylight followed by 2 weeks of darkness. This is a problem for both SFO and PV/LED systems. Since plants have life spans longer than two weeks, there is great value in having a light source that can operate without sunlight on the Moon. The effect of 14 days of continuous darkness has been studied by several laboratories. Chard et al. (2002) found that the addition of a PPFD of only 5 to 10 μmol m^{-2} s^{-1} was sufficient to keep plants healthy during the 14 day lunar dark period. Tuskegee University studied the effect of 14 days on continuous darkness on sweet potatoes and also found that the addition of 7 to 10 μmol m^{-2} s^{-1} during a 14-day simulated lunar night resulted in a minimal reduction in yield (Mortley et al. 2016). The effect of low level lighting on ESM was analyzed by Drysdale and Bugbee (2003) and found to be cost effective. A low level of lighting during the lunar night would not be available from an SFO system.

Though electric lighting systems are already lighter on Mars, they have the additional benefit of being able to operate during a large dust storm if powered by nuclear reactor. Currently, a high-TRL nuclear reactor 'Kilopower' is being developed that is expected to produce 10 kW of power at a power equivalency of 155 kg per kW (Rucker 2015). Although this is an order of magnitude greater than PV power equivalencies, it can operate at all times. This will make electric systems even more competitive.

Another important consideration is the ability to spectrally change LED lighting systems over the crop lifecycle. The electrical system can be tuned to have a higher red-to-blue photon ratio than sunlight. Red photons have lower energy than blue photons and therefore have a lower power requirement at the same PPFD. The SFO lighting system has a fixed spectrum with 27% blue photons, which tends to reduce yields (Snowden et al. 2016). Photosynthesis can be calculated using yield photon flux (McCree 1971; Sager et al. 1988) rather than the traditional photosynthetic photon flux. This analysis shows that a 95:5 red-to-blue ratio as described in this paper is about 10% more photosynthetically efficient than sunlight, and the increased leaf expansion can further increase photon capture and yield (Snowden et al. 2016). While some studies have suggested that a 10% blue spectrum is required for normal plant growth, recent evidence suggests that at a higher PPFD, 5% blue photons is adequate (Goins et al. 1997; Yorio et al. 1998; Yorio et al. 2001). This lower fraction of blue photons reduces the ESM of the electric lighting system.

Both systems have the ability to include far-red photons (700 to 750 nm). These photons have recently been shown to have a photosynthetic efficiency equal to traditional photosynthetic photons (400 -700 nm) (Zhen and Bugbee 2020), and they can increase stem elongation and leaf expansion (Park and Runkle, 2017). These photons are even lower energy than red photons, so their addition has the potential to decrease the ESM of both systems. Unfortunately, our preliminary data indicates that they increase stem elongation more than leaf expansion in most species so the addition of far-red photons must be carefully regulated. This regulation is easily facilitated by a PV/LED system.

The PV/LED system is more flexible than the SFO system. It facilitates optimization of 1) the position of the emission source to increase photon capture, 2) photoperiod regulation, and 3) spectral distribution and intensity. These advantages and a lighter mass make a PV/LED approach the preferable system. We look forward to further optimizing photon delivery systems for space-based applications.

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