***3 Use of lunar resources on Earth***

Although a developing cis-lunar economy will necessarily yield wider economic benefits to the Earth as well, the opportunities for lunar resources to make a *direct* contribution to the world economy in the foreseeable future are quite limited. This is because our planet contains the same basic mix of elements as the Moon and the rest of the Solar System, many of them in higher localised concentrations (i.e. ores) and, unlike the Moon, already has a well-developed infrastructure for extracting and refining raw materials. There appear to be three possible exceptions to this general observation, which I discuss below: (i) rare elements for which the market value may render lunar sources economic; (ii) lunar-derived energy sources; and (iii) materials for which the environmental cost of terrestrial mining may make lunar sources more attractive.

***Lunar sources of rare elements.*** Much thought has been given to identifying materials for which their present high market value may render the exploitation of extraterrestrial sources economic (e.g. Lewis, 1996). The PGMs usually feature prominently in these discussions, with near-Earth asteroids (NEAs) identified as possible sources (Lewis and Hutson, 1993; Kargel 1994; Elvis, 2012). However, the possibility of finding ‘crashed’ iron meteorites on the Moon (e.g. Wingo, 2004; Wieczorek et al., 2012; see the discussion in Section III(5) above) means that lunar sources should not be excluded from consideration. Moreover, although the Moon has a much higher gravity well than do NEAs, it has at least two advantages which may off-set this relative inconvenience. Firstly, it is much closer than any NEA (many NEAs, while they may transiently pass close to Earth, spend most of their orbits at much greater distances and have long synodic periods). Secondly, as discussed above, in the coming decades a local infrastructure may develop on the Moon to support a mix of scientific, industrial and tourism activities, and this could provide local support for mining operations of a kind unlikely to be available at NEAs. Indeed, the presence of such a local infrastructure may reduce the cost and risks of extracting these materials on the Moon to the point that the Moon becomes economically more attractive than NEAs.

One potentially important future application of lunar PGMs may prove to be as catalysts for a future fuel-cell-enabled hydrogen economy on Earth (e.g. Wingo, 2004), where the high cost of these materials is currently a limiting factor (Debe, 2012). Ultimately, whether or not lunar (or indeed any extraterrestrial) sources of PGMs, or other rare and expensive materials, will prove economic in the long-run will depend on whether the prices that these materials can fetch on Earth will remain sufficiently high in the face of a significant increase in supply. Addressing that topic would require an economic analysis beyond the scope of the present paper.

***Lunar sources of energy.*** Most discussion of lunar energy sources for planet Earth have focussed on the possible use of solar wind-derived 3He in terrestrial nuclear fusion reactors (Wittenberg et al., 1986; Kulcinski et al., 1988; Taylor and Kulcinski, 1999; Schmitt, 2006; see Section III(2) above). However, there are a number of serious problems with this scenario. Firstly, nuclear fusion has not yet been demonstrated to be

a viable source of energy on Earth, and current large-scale experiments (such as the international ITER facility due to become operational in 2028; Butler, 2013) are based on deuterium-tritium (D – 3H) fusion rather than D ‒ 3He. An oft-stated advantage of 3He fusion is the lack of neutrons produced by the primary reaction (which would induce radioactivity in the reactor structure), but as some level of D-D fusion cannot be prevented in a D – 3He plasma (Close, 2007) this claimed advantage is often exaggerated (it would apply to pure 3He – 3He fusion, but that reaction is requires much higher temperatures to initiate).

Even assuming that D ‒ 3He fusion *is* found to be technically practical as a power source, the low concentration of 3He in the lunar regolith (Section III(2)) implies that mining very large areas would be required. In order to estimate the quantity of regolith that would need to be processed we need to estimate the end-to-end efficiency of converting lunar 3He rest-mass energy into electricity on Earth. Conventional power stations generally have efficiencies of about 30%, but advocates of 3He fusion estimate efficiencies of 60 – 70% for this process based on the (hypothetical) direct electromagnetic conversion of the fusion product energy into electricity (Kulcinski et al., 1988; Schmitt, 2006). However, this figure ignores the efficiency of extracting 3He from the regolith; as discussed in Section III(1), this will require heating large volumes to about 700°C (which would itself consume about 5% of the energy obtained from the fusion of the released 3He unless efficient ways of recycling heat from one regolith batch to another can be implemented), and complete efficiency in the release, collection, and purification of 3He can hardly be expected (~80% may be reasonable based on the figures given by Kulcinski et al., 1988). Furthermore, transport to Earth will also require energy, as will the extraction, processing and transport of D obtained from sea water to act as a reaction partner (which has been entirely neglected here). Bearing all this in mind, it is hard to see how the end-to-end efficiency could exceed 50%, and may be much less.

Annual world electricity consumption is predicted to rise to 1.4×1020 J (40,000 TW- hours) by 2040 (US Energy Information Administration, 2014), and if lunar 3He were required to produce, say, 10% of this then, for an assumed overall efficiency of 50%, about 500 km2 of high-concentration (i.e. 20 ppb 3He) regolith would need to be processed every year down to a depth of 3 meters. Note that, owing to the ubiquitous presence of craters and other obstacles on the lunar surface, only a fraction of a given surface area (estimated at 50% by Schmitt, 2006) will actually be amenable to processing, and allowing for this the highest concentration deposits of this non- renewable material (Fig. 6) would last for about 2000 years. Producing *all* of Earth’s anticipated mid-21st century electrical energy requirements from lunar 3He would require processing 5000 km2 per year, which may be impractical, and then the accessible reserves would hold out for only about 200 years.

It therefore seems that, at best, lunar 3He could only ever make a relatively small contribution to Earth’s total long-term energy needs. Given the uncertainty as to whether the world economy will ever come to rely on nuclear fusion as a power source,

and the practicality of 3He fusion in particular, not to mention the scale of the investment that will be required to extract lunar 3He and its non-renewable nature, it appears at least premature to identify lunar 3He as a solution to the world’s energy needs. That said, assuming the question of practicality can be resolved, the high energy density of 3He as a fuel (~5.8×1014 J kg–1 for D – 3He fusion), and its corresponding potential value (several million US dollars per kg at current wholesale energy prices, with the exact value depending on the energy sector with which the comparison is made; US Energy Information Administration, 2014), may nevertheless result in the identification of economically viable, if relatively small-scale, future applications. Possibilities might include space-based fusion power systems, and mobile low- radioactive fusion reactors for use on Earth (e.g. Schmitt, 2006). Moreover, there is currently a shortage of 3He on Earth for non-fusion applications (e.g. Kramer, 2010), and lunar 3He could possibly help satisfy this demand. As 3He will automatically be released as a by-product of extracting other, more abundant, solar wind-implanted volatiles from the lunar regolith (Section III(1)), it is worth keeping an open mind to such possibilities.

As far as the long-term energy requirements of planet Earth are concerned, it would appear more logical instead to invest in developing genuinely inexhaustible energy sources on Earth itself. Possibilities include some combination of D-T and D-D fusion, and/or solar, tidal or geothermal power, supplemented if necessary by space-based solar power systems. As noted above, lunar resources could contribute to the latter either by supporting the construction of geostationary solar power satellites (Maryniak and O’Neill, 1998), or through the construction of solar arrays on the lunar surface and beaming the energy to Earth (Criswell, 1998; Criswell and Harris, 2009). Just to put this latter point in perspective, covering a given area of the near-equatorial lunar surface with solar panels would yield as much electrical energy in 7 years (3×1010 J m–2, assuming a conservative 10% conversion efficiency) as could be extracted from all the 3He contained in the 3m of regolith below it (assuming 20 ppb 3He and an optimistic 50% overall efficiency). If the conversion efficiencies were the same (say 20% each, which in practice might not be unreasonable) then solar energy would out produce 3He in just 1.4 years. But whereas, once extracted, the 3He would be gone forever, the solar power would be continuous. Looked it from this perspective, it would be far more efficient to beam lunar solar energy to Earth than it would be to extract, and physically transport to Earth, 3He for hypothetical fusion reactors which have not yet been shown to be practical.