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Solar Landfills: Economic, Environmental, and Social Benefits

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Ideally suited for hosting large solar photovoltaic arrays feeding electricity into the grid, closed landfills will play a significant role in the undergoing energy transition from fossil-fuel and nuclear energy to renewable energy. Aimed at sustainability scholars and policy makers, this study identifies the economic, environmental, and social benefits of solar landfills, suggesting avenues for the massive transformation of hazardous landfills into renewable-energy-generation plants. Thus, the landfills no longer pose threats to human health and to the ecosystem.

1. Introduction

The functionalization of closed landfill sites with solar photovoltaic (PV) modules is a sustainable-development option actively pursued across the world.[1] In a recent seminal study focusing on Europe, Szabó et al. conservatively estimated the additional PV power that could be installed on large closed landfill sites only in the territory of the European Union to be in the range of 13 GW .[1]

Generally comprised of low-slope large areas of terrain filled with all sorts of waste, landfills are usually located near cities with high energy demand and are served by high-capacity electric transmission lines. Both features make them particularly well suited for solar PV development from a technical and economic viewpoint. "There has never been a more opportune time for municipalities to develop solar photovoltaic systems on landfill sites", reads the introduction to the guide for the development of solar landfills in Massachussets published by the State's energy agency in 2012.[2] The United States indeed pioneered using PV in municipal waste landfills,[3] including the first use of a 130 kW flexible PV geomembrane in San Antonio (Texas), which began operation in April 2009.[4]

Besides the compelling economics, several environmental and social reasons justify the rapid solarization of landfills in both developed and developing countries. Together, they are the subject of this study aimed at policy makers as well as sustainability scholars and professionals. The study proceeds as follows. It first discusses the technical aspects in light of both recent technical progress and actual performance of selected solar landfills. We then present the main economic, environmental, and social advantages, referring again to selected case studies. Finally, we discuss the obstacles to complete solarization of closed landfills in the context of the transition to the circular bioeconomy,[5] offering advice to policymakers on how to tackle the obstacles identified.

2. Technical Aspects

In the emerging circular economy what was previously considered "waste" such as municipal solid waste actually consists of valuable materials to recycle and compost (Figure 1).[6]

In a circular economy, furthermore, energy is generated from renewable energy sources such as water, sun, and wind, with energy from PV, in particular, experiencing an exceptional and largely unforeseen global boom during the last decade .[7] In this context, the PV industry is undergoing consolidation, with all major players now based in China,[8] including manufacturers of thin-film modules, who recently acquired most former small manufacturers of modules using CIGS (copper indium gallium diselenide) based in the US and in Germany.

Modern PV technology offers distinctive versatility, with both rigid and flexible solar modules available for landfill solarization, even though almost all landfills hosting a PV plant constructed in the last decade in Europe, the US, or Asia use conventional glass modules with Si, with a 5 MW plant currently (late 2017) being installed in Malta's former municipal landfill using 22000 multicrystalline Si modules.[9]

A recent study of the team led by Szabó mentioned above identified i) terrain stability, which is related to the method of waste compacting and ii) nature of landfill sealing as the two decisive factors in selecting the appropriate PV technology for each of the landfills.[1] In brief, glass PV modules in crystalline Si with conventional mounting structures would

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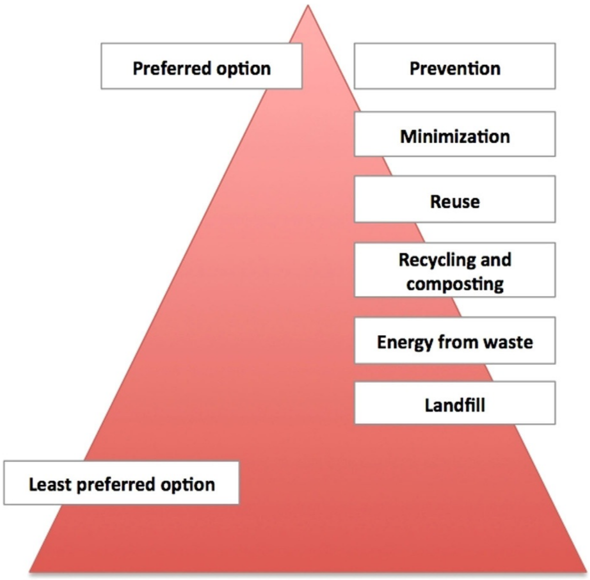

Figure 1. Hierarchy of priorities for sustainable municipal waste management. Adapted from Ref. [6], with kind permission.

be best suited for waste-compacted sites whereas thin-film PV geomembrane flexible systems would be ideal for non-sealed or non-compacted landfill sites. The team assumed 17% and 10% as, respectively, the photovoltaic conversion energy efficiency levels for Si and thin-film modules, assuming a 50% landfill utilization for the PV geomembrane, even though when they used geo-orentation analysis for ten real closed landfill sites in Hungary, they found that “in most cases” the real utilization rate for PV geomembrane was 90%.

Both rigid and flexible solar module technologies, however, are undergoing rapid improvement in PV conversion efficiency, which must be taken into account when planning the massive landfill solarization proposed in this study. Dealing with glass modules, both 72-cell monocrystalline silicon (mc-Si) and large thin-film modules using cadmium telluride[10] of nameplate power exceeding 400 W will shortly (in 2018) become the industry’s standard for utility-scale PV plants.[11] These larger modules of almost twice power compared to conventional 250 W silicon panels will cut the balance-of-systems (BOS) costs, thus enabling quicker and cheaper installation of large PV arrays.

On the other hand, because of better performance under cloudy sky and with higher temperatures, the use of thin-film technologies allows generation of more energy per watt installed compared with conventional crystalline Si modules with the same power rating.[12] For example, despite of non-optimal tilt and orientation, a 752 kW PV plant using triple-junction solar cells using amorphous silicon (a-Si) over a geomembrane over Rome’s Malagrotta landfill (Figure 2), generated 1432 kWh of energy per kW installed in its first year,[13] which is an energy yield value closer to that of PV systems installed in Sicily rather than in central Italy, where a conventional PV system on average generates annually 1300 kWh per kW^{-1}.

Figure 2. Part of the 752 kW PV flexible array at Rome’s Malagrotta landfill. Reproduced from Ref. [13], with kind permission.

The main problem with the above modules using a-Si installed in early 2008 is that their low standard-test-conditions (STC) efficiency ($\eta = 6\%$) required a surface area of 28 m^2 to achieve 1 kW of nominal power, which partly explains the low utilization rate of the flexible technology in landfills despite the unique advantages offered by theses light and flexible modules. However, since late 2012 Italy hosts near the city of Treviso the first solar landfill using 12.6% flexible modules utilizing CIGS as photoactive material (Figure 3).[14] The 998 kW PV array, in detail, consists of 3630 flexible modules (275 W each) organized in five different subsystems each consisting of 726 modules fixed to the geomembrane in synthetic rubber [ethylene propylene diene monomer (EPDM)] with velcro.

Figure 3. Tiretta landfill near Treviso, Italy. The CIGS solar modules on top of the geomembrane are clearly visible. Satellite photograph uisng Google Earth, 2017.

In further detail, the company operating the Tiretta solar landfill has estimated an energy production of 4 146 000 kWh for the first four years (1 January 2013–31 December 2016) whereas actually the PV array has produced 3 813 400 kWh, about 8% less than planned, with an effective production of 1273 $kWh\,kW^{-1}$, largely ascribed by the company to the flat nature of the landfill, which eases the accumulation of debris over the landfill surface.[15] Besides the 8% lesser energy yield, however, the PV geomembrane did not cause any problems, requiring very little maintenance, with the company currently exploring the possibility to install similar systems in other landfills managed in its region (Veneto).

In the meantime, the efficiency of todays flexible modules using CIGS has increased to 17.7%,[16] which exceeds the conversion efficiency of several conventional polycrystalline Si modules. A similar exceptional trend of the efficiency was observed for the most widely used thin-film PV technology (based on CdTe) with modules delivered to customers in 2009 having 10.5% efficiency[17] and those delivered by the end of 2016 having an efficiency of 16.9%.

Now as highly efficient thin-film modules have become commercially available and in combination with geomembrane, they will quickly become the technology of choice for solar landfills. Installed over the capped layer of landfills covered by a thin earth layer, rigid and heavy PV modules require non-invasive ballasted mounting systems to avoid ground penetration and rupture of the waste capping, which would release underlying contaminants and, even worse, allow water penetration and leachate formation.

On the other hand, the geomembrane easily follows to the contours of the landfill, enabling sealing and solarization of landfills of any slope, including sloped landfill sites such as that near Atlanta (Figure 4) where a 1006 kW array of flexible modules using a-Si over a thermoplastic polyolefin (TPO) geomembrane was completed in 2011.[18] Consisting of 6984 PV laminates (each of 144 W nominal power), the system was expected to generate 1.3 million kWh in the first year, retaining 90% of the original production after 20 years.

The flat configuration and the polymeric nature of the flexible modules makes them intrinsically resistant to wind, lightning, and earthquakes. Their weight is continuesly improved, with the distributed load being decreased from 3.6 $kg\,m^{-2}$ of the first modules using a-Si to current 2.4 $kg\,m^{-2}$ for flexible CIGS modules.[19] Such lightweight flexible modules are easily and quickly installed directly onto the membrane cover using adhesive or velcro technology (Figure 5). Not only is penetration prevented, but water penetration is reduced to minimal levels, protecting the environment by avoiding leachate formation while enabling collection of clean meteoric water (see the water reservoir in the bottom part of the picture in Figure 4). UV radiation-resistant polymers making up the geomembrane caps usually consist of EPDM or TPO, such as linear low-density (LLDPE) and high-density polyethylene (HDPE), or flexible polypropylene (fPP);[20] these caps haveng very long predicted exposed lifetimes varying between 33 and 42 years.

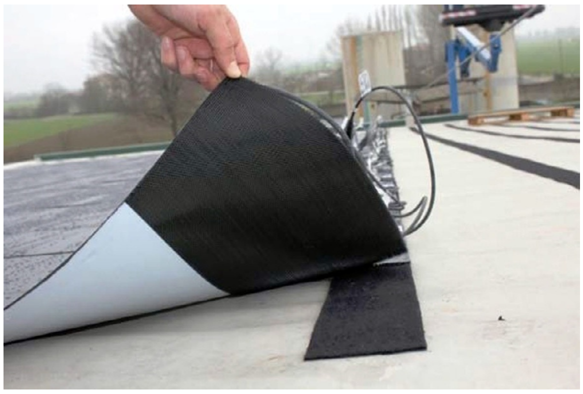

Figure 5. CIGS solar modules in the Tiretta landfill adhering to the EPDM geomembrane with velcro. Image courtesy of Contarina SpA.

Actually, the geomembrane technology is so advantageous and versatile that it is successfully used also for solar landfills using conventional rigid modules. For example, the 1 MW array installed in 2014 over the Hartford landfill located at the outer banks of the Connecticut river (Figure 6) uses an innovative three-component closure system that greatly re-

Figure 4. Hickory Ridge landfill near Atlanta, hosting a 1 MW PV wiht solar-exposed geomembrane on the southwest and southeast slopes of the landfill. Image reproduced from Wikipedia, with kind permission.

Figure 6. Hartford landfill in Connecticut hosting a 1 MW photovoltaic plant with rigid modules on top of synthetic turf. Image of Connecticut Materials Innovation and Recycling Authority, reproduced from Ref. [21], with kind permisssion.

duces the environmental impact to the river and enhances water quality.[21] It is the impermeable geomembrane cover that will alleviate problems of odor and air pollution. It is worth noting here that ductile geomembranes (mostly composed of LLDPE or fPP, which can follow the profile of the different waste settlements without inducing stresses—that could initiate stress cracking—can better accommodate the strains associated with different settlements) are used to cap landfills both to prevent the ingress of rainwater and to capture and remove landfill gas.[22] In detail, the system uses a synthetic turf attached to the geomembrane covering the landfill and hosts the rigid PV modules on ballasted trestle-mounting systems placed on top of the turf. The turf can be freely walked on or driven across by light rubber-tire vehicles without product damage, with reduces the repair and maintenance costs while offering a largely improved aesthetic aspect n compared to exposed geomembrane systems. Indeed, it is noteworthy that one bidder company for the Hartford's landfill proposed a TPO exposed membrane with chemically welded thin-film PV modules on top of this capping installation as the solar collector. The competing proposal, which eventually won the bid, instead proposed the application of a permeable synthetic turf carpet placed over a geomembrane to serve as a platform for the PV array.[23]

The geomembrane PV technology with the PV laminate on top replacing conventional capping can either be used in the exposed geomembrane configuration or with a more aesthetically pleasant synthetic turf layer (Figure 7). In both cases, the drainage layer, the vegetative support soil layer, and topsol layer bearing grass of conventional capping are no longer needed. In conventional closure the soil cover acting as the ballast to the geomembrane is quickly eroded during storms, requiring soil replacement to avoid cap failure. In contrast, the geomembrane cover does not rely on grass and soil to cover the underlying geomembrane liner.[4]

3. Environmental and Health Benefits

Three main health and environmental benefits support and justify the use of closed landfill sites for utility-scale PV generation. First, landfills provide large space not competing with agricultural use. Second, very often existing landfills pose a serious threat to human health and to the ecosystem. Third, utility-scale generation of PV electricity directly results in avoided particulate emission from conventional thermoelectric plants with direct impact on public health. All these aspects deserve further attention.

3.1 Fruitful use of unproductive space

The generous feed-in-tariffs (FiT) public incentives made available to the owners of PV plants in Europe starting from Germany and Spain in the early 2000s through Italy, the United Kingdom, and several other countries led many farmers and city councils to rent agricultural land and rural landscape to host large PV parks. This has resulted in local citizen protests across Europe[24] and has somehow tarnished the public image of the photovoltaic technology even though covering the full demand of electricity of 25+5 member states of Europe (not taking into account the need to cope with the variability of the solar resource) would require covering only 0.6% of the overall territory.[25]

In the forthcoming unsubsidised massive adoption of solar PV that will take place in Europe's countries where significant PV power has been installed thanks to the above mentioned FiT incentives, rooftops and unused terrain of low or negative value will be used for large-scale solar electricity generation. In Italy only, covering the 10.5 million one- or two-family homes and 1 million industrial rooftops already available with solar modules would provide the country with 100 GW of additional power, enough to generate >40% of the country's electricity demand.[26] Likewise to rooftops, landfills offer plenty of space available at no cost and easy linkage of the PV array to existing electric connections.

3.2 Environmental and health concerns

Most landfills require environmental remediation because most landfills were in use when no environmental and health protecting legislation dictated what could be landfilled and what could not. For example, the Tiretta landfill near Treviso hosting 9000 tonnes of municipal "dry" (i.e., devoid of the organic fraction) waste in addition to 296000 tonnes of industrial waste, a few years after its inauguration in 1994 was found to contaminate the water aquifer with bromacil and other toxic compounds. Subsequent investigations carried out by the public company managing the landfill in place of the bankrupt private company identified the release of leach-

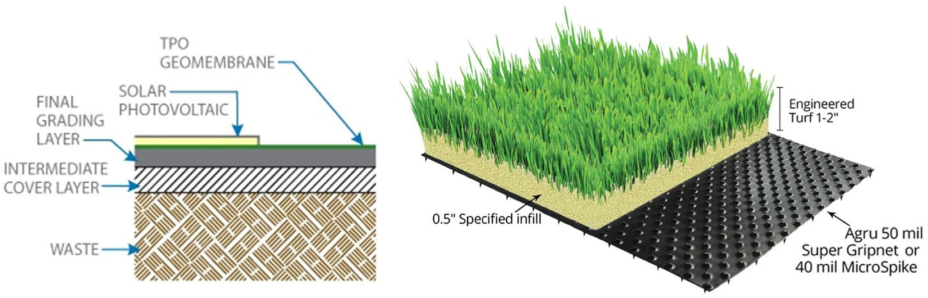

Figure 7. Geomembrane technology for landfill closure with flexible PV modules on top of the exposed geomembrane (left, image courtesy of HDR Engineering) or with synthetic turf layer (right, image courtesy of AGRU America).

Figure 8. Environmental remediation works carried out in 2011 at the Tiretta landfill in Italy. Image courtesy of Contarina SpA.

ate through a hole on the bottom membrane with meteoric water penetration through the perforated cap membrane as the source. In 2011, thus, the company commissioned extensive environmental remediation works (Figure 8). The deteriorated capping was removed and a >50 cm layer of low-permeability clay earth was placed over the waste, with insertion of new biogas and leachate recovery systems. Eventually, a new EPDM synthetic rubber geomembrane was anchored over the earth clay and a new conduit system to collect meteoric water was constructed along with a new water reservoir system to collect and distribute rainfall water close to the landfill. In 2012, the exposed geomembrane was equipped with flexible solar modules using CIGS mentioned above. Ever since, the landfill has been closely monitored and no further leaching of toxic compounds or bad odors owing to release of mercaptans or hydrogen sulfide were reported.

Similar environmental remediation works were preformed in most solar landfills built so far across the world and are generally planned for new solar landfills. From India[27] to Germany,[28] from the UK[29] through several African[30] countries, environmental contamination from municipal waste landfills is indeed an ubiquitous environmental and health issue.[31]

3.3 Environmental and health benefits of PV-electricity generation

Generating PV electricity literally saves human lives and prevents illnesses, ending the pollution of thermoelectric electricity generation. Converting the current coal-fired power to PV power (755 GW of photovoltaic power needed) of the USA alone would result in 51 999 lives saved per year.[32] Fine particulate matter formed during coal and heavy-oil combustion causes cardiovascular and respiratory disease and cancer. Comprised of 10 μm (PM_{10}) or less ($PM_{2.5}$) toxic particles (major components are sulfate, nitrate, ammonia, sodium chloride, black carbon, mineral dust and water), particulate matter (PM) penetrates deeply into the respiratory tract where it becomes lodged permanently.[33] Small-particulate pollution has health impacts even at very low concentrations—indeed no threshold has been identified below which no damage to health is observed. Therefore, the guideline limits presented by the WHO in 2005 aimed at achieving the lowest concentrations of PM possible.

Air pollution is the single largest environmental risk today, with 3 million premature deaths per year linked to outdoor air pollution in 2012, and 87 % occurring in low- and middle-income countries.[34] There is a close, quantitative relationship between exposure to high concentrations of PM_{10} and $PM_{2.5}$ and increased mortality or morbidity, both daily and over time. Conversely, when concentrations of small and fine particulates are reduced, related mortality is reduced.

Generation of PV electricity produces no emissions or generates any waste and has an excellent environmental footprint,[35] which is improved year after year as the amount of photoactive material to generate power is reduced and the photovoltaic conversion efficiency is increased. For example, the amount of crystalline Si used in Si-based solar cells during the last 12 years has gone from around 16 $g\,W^{-1}$ in 2004 to less than 6 $g\,W^{-1}$ in 2016 because of increased efficiencies and thinner silicon wafers.[36]

4. Economic and Social Benefits

Solar PV systems installed at closed landfills provide immediate economic and social benefits in the form of financial revenues for the energy sold, prolonged savings attributable to reduced maintenance costs, job creation, and tax reduction.

4.1 Financial revenues

The first solar landfills connected to the grid in Europe generated revenues thanks to the FiT incentives, that is, receiving a generous tariff (>0.2–0.4 € per kWh) for each kWh generated. For example, the Tiretta's landfill owners receive 0.2354 € per kWh. In todays unsubsidised scenario in which complete solar PV systems are installed at 1000 € per kW, however, the revenues for solar landfills will originate from selling energy back to the grid.

Energy selling can take place through power-purchase agreements, for example, signed with the regional power grid (as in the case of Connecticut's Hartford landfill), or directly on the day-ahead market. In that respect, solar electricity producers capable of forecasting weather and estimating the actual energy production of the subsequent day, rather than selling electricity at a low and flat price on the zonal electricity market, become able to place offers on the day-ahead market following demand because of accurate prediction of the plant production based on meteorological forecasting.[37] More revenues originate also, for those landfills burning biogas to generate electricity, from the enhanced amount of biogas extracted from the landfill whereas the electricity required for pumping the biogas is self-produced through the solar modules.

4.2 Lower installation and maintenance costs

The landfill land is free. In the case of rigid PV modules installation, both mounting and labor, will be more expensive in comparison to installation over conventional land as use of heavy machinery would be restricted. This is not the case for PV geomembranes in which installation, again both labour and mounting, is quick and straightforward (see above).

Most closed landfills are connected to the electricity grid through connections of significant capacity (several MW) to transfer large quantities of electricity, as often electricity was produced at landfills burning biogas freely produced by anaerobic fermentation of the organic fraction of municipal waste.

In closed landfills these biogas-fired thermoelectric plants are either closed (for example at Rome's Malagrotta site) or running at reduced capacity leading to under-utilization of the existing connection. Furthermore closed landfills are generally fenced and monitored, which reduces the security costs of conventional solar parks, which in turn are the frequent theft target of criminal organizations.

Post-closure maintenance cost savings are also significant because the mowing, fertilizing, erosion control, drainage layer, and cover maintenance costs in landfills with traditional closure vanish with the solar energy cover. A comparison of initial closure and long-term care costs of a solar energy cover versus a traditional landfill in the US for a 30-year period, carried out by an engineering company developing PV geomembrane systems in the US, claims that a solar energy cover system involves 9 times lesser costs of the traditional closure.[4]

4.3 Social benefits

Investing in solar landfills, municipalities, and public authorities will support economic growth through job creation and local tax reduction. This is an extremely important aspect of solar PV electricity, which is of crucial relevance. For example, in Italy a small city uses since 2013 the FiT incomes of a 13 MW solar PV array built on greenhouse rooftops to eliminate a tax and save its inhabitants and local companies a significant amount of money.[38]

Indeed, whereas closure and maintenance of a conventional landfill presents only costs ultimately beared by the community through taxation, the solar landfill provides valued environmental and health services while generating economic value in the form of money obtained selling electricity. The high economic costs to properly manage closed landfill sites, or portions of said landfills that are already saturated, explains why in several regions, even in Europe, residents lament the poor health and environmental conditions. In Sicily, for example, the residents of two landfill-confining cities have been protesting for years agains the odors and the pollution created by the second largest landfill, near the large city of Catania (Figure 9).

Figure 9. Citizens of Misterbianco, in Sicily, protesting in 2016 against the confining landfill contaminating the environment and threatening health. Image courtesy of http://danilofesta.wordpress.com.

In 2014 alone did the landfill release some 4.2 million m^3 of biogas generated along with stinking mercaptans and hydrogen sulfide and several other toxic compounds into the atmosphere .[39] In the UK, there are 1264 historic landfill sites in the coastal zone with the risk of being flooded during extreme weather events and coastal erosion.[40] In Bucharest, where currently 95% of the 272 kg of annual municipal waste per capita is stored in landfills,[41] the large Boului–Glina landfill, which started operation after the 1977 earthquake, is interested in performing environmental remediation works since 2008.[42] In Australia, the cities of Brisbane, Victoria, and Adelaide already commissioned feasibility studies to undertake large PV installations in the their landfills.[43] The world's largest country, Russia, hosts 4000 landfills in which 95% of the 48 million tonnes municipal solid waste is disposed every year, with 30% of sites in 2010 not meeting sanitary requirements.[44] These are just selected, representative examples in which the use the PV geomembrane technology along with environmental remediation will provide the needed financial revenues to support the long-term monitoring and management activities required to remediate the legacy of the throwaway society, the landfill.

5. Outlook and Conclusions

Referring to selected case studies across the world, and putting discussion in context of the latest developments concerning photovoltaic (PV) energy and technology, this study identifies the environmental, economic and social benefits brought about by the solar transformation of existing landfills.

Landfills impact public health and the environment, requiring suitable managing and constant monitoring, namely costly activities that consume significant financial resources every year for decades. Now that the efficiency of the latest thin-film modules in flexible format has reached and even surpassed the conversion efficiency of multicrystalline Si modules, we have argued in this study that a PV geomembrane using said thin-film solar cells will become the technology of choice.

The numerous benefits discussed far outweigh the costs of the financial investment required, especially now that the cost of solar PV modules has fallen to unprecedented low levels, providing a striking example of "techno-ecological synergy", namely of mutually beneficial relationship between technological and ecological systems as emphasized by Hernandez et al.[45] With the quick drop in price of PV solar cells and modules, the main factor hindering the growth of installation of PV systems on landfill sites, namely the high investment cost, has vanished. Actually, the drop in price has been so rapid (for example beween September 2013 and July 2017 the price of crystalline modules in Germany has gone from 0.74 to 0.45 € per Watt, that is, ≈40% reduction)[46] that managers at public and private landfills are still convinced that costs are still high and payback time long, which explains why the current usage of landfill sites for solar PV installations is so limited in comparison to the vast number of existing landfills (most large cities have landfill sites).

In brief, as the solar economy determined out by Scheer[47] more than a decade ago rapidly unfolds ahead of mankind, it is instructive to notice that waste and landfills, which epitomize the poor functioning of the open-loop economy, terminate their existence as a thing of the past, ultimately providing their last service as platforms for clean energy generation. Germany, where all landfills are now closed, recycled 317.7 million out of 402.2 million tonnes of its total waste volume in 2015[48] (total waste includes waste generated by the construction industry, production facilities, and municipalities).

The world will progressively follow, as the global economy turns into a set of closed-loop, interconnected production cycles, with countries creating new research and educational centres for the education of professionals capable to proactively act based on cross-disciplinary knowledge.[49] The arguments of this study will hopefully contribute to accelerate this progress.

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Conflict of interest

The authors declare no conflict of interest.

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