



A methodology for maximizing the benefits of solar landfills on closed sites



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ABSTRACT

Local urban planning has become concerned over clean energy technologies development on greenfield land that may lead to competition in land use. Solar photovoltaic systems on agriculture land is an indicative example of this disputed strategy. At the same time closed landfills and their post-closure management pose environmental, economic and land value concerns at the local authorities. In the present work we analyse the concept of solar photovoltaic system installation in closed landfills. This practice has already received attention and the present article provides an overview of existing installations as well as assessment of the existing potential. Moreover, it introduces a methodology that geoanalyses closed sites, evaluates them in a hierarchical manner and suggests the appropriate PV technology for each site. The methodology has been applied in Hungary and revealed that 450 MWp of solar could be deployed in Hungarian closed landfills. EU-level projections provide estimations for the potential to range around 13 GWp. Such an approach may become a forefront instrument in the local, bottom-up sustainability policy planning.

1. Introduction

The present paper puts forward a set of projects in industrial symbiosis of the electricity and waste management sectors. Sharing utilities and sites derives mutual benefits for both sectors and the environment. Despite landfilling being the least preferable option according to the waste management hierarchy and should be limited to minimum, this was the most extensively used option in the past [1]. In order to align with the waste management requirements [2–4], several countries and EU member states (MS) have ceased the operation of landfill sites. However, many of the old waste disposal sites have not been managed, but simply came to a standstill. Their owning authorities (municipalities, counties) often do not have neither the expertise nor the resources and required personnel to implement proper management. Nonetheless, closed sites are a potential long-term environmental hazard if not managed systematically. Such sites need proper management even if they seem to be inert and that explains the regular fines imposed to EU Member States [5] when violations are observed.

In the present work we analyse a win-win solution by converting the detrimental disposed waste infrastructure to scale up renewable energy

(RE) in the electricity generation portfolio. This can be achieved by developing solar landfills in sizeable brownfield areas of former waste deposits. Brownfield redevelopment for energy purposes is currently in the spotlight and methods to distinguish the most advantageous sites have been developed [6]. We evaluate the inventive concept that suggests the installation of solar photovoltaic systems (SPVS) in closed landfill sites, combining renewable electricity production with resource-efficient land use. The specific purpose of this paper is to present technical information regarding the characteristics, the advantages and the challenges of this alternative scheme. We developed a GIS-based methodology that evaluates the available landfill sites and highlights those suitable for application of the proposed scheme. The methodology was then tested on a large data-set that comprises 2568 closed landfills in Hungary. Moreover, it extrapolated the outcome to EU-scale, in order to provide an estimation of the available potential for solar landfills in EU.

The obtained information is mainly addressed to stakeholders, developers and local-regional authorities. In order to identify a win-win solution for these challenging segments, the different factors affecting photovoltaic (PV) developments are analysed along with shortcomings

Abbreviations: CLC, Corine land cover; DEM, Digital elevation model; DSO, Distribution system operator; EU, European Union; FIT, Feed-in tariff; GIS, Geographic information system; HEPURA, Hungarian energy and public regulatory authority; LFG, Landfill gas; LCOE, Levelised cost of electricity; MCA, Multi-criteria analysis; MS, Member States EU; NMS, New Member States; PV, Photovoltaic; RES, Renewable energy sources; SPVS, Solar PV system; TSO, Transmission system operator; WtE, Waste-to-energy

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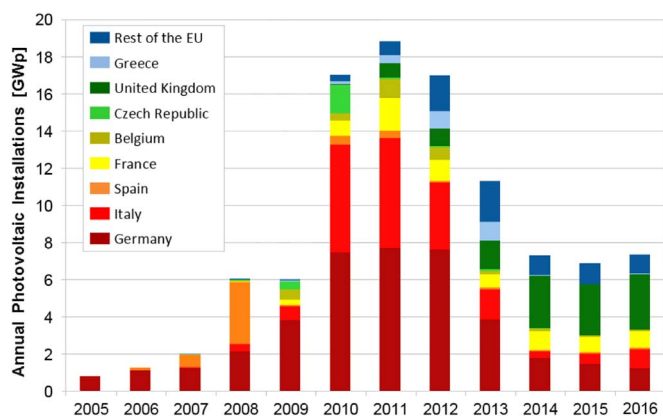


Fig. 1. The PV installation market trends in the EU. Source: Authors' compilation [7,8].

in waste management. The study reveals business opportunities to succeed with higher PV penetration in countries lagging behind in PV development.

2. Literature survey and existing applications

2.1. Solar PV development in the European Union

Among MS, PV installations showed very diverse trends during the last decade. While some countries showed only moderate development with no real take-off on solar capacities, others (e.g. Italy, Spain, Greece and Germany) showed an unprecedented PV growth that was suddenly disrupted. PV installations in EU between 2009 and 2013 were clearly flourishing. PV growth rate over the decade was >50%, making solar one of the fastest growing power generation sectors in Europe. Since then, the tendency has changed. With the exception of UK, annual PV installations have declined in the leading EU markets (see Fig. 1).

Aside from the leading EU markets, MS have shown a mixed picture. Smaller PV markets showed some growth, but they started from a very low basis. A closer look at the various segments of the PV market reveals that overall SPVS installations (rooftop and utility scale) evolved very differently in the MS. In Germany, Italy and Greece SPVS has provided over 7% of the annual total electricity. However, in the rest of EU the share of solar in electricity production is less than 3%. While PV installations in Belgium and the Czech Republic decreased, the Romanian market peaked in 2014. The PV markets in Croatia, Poland, Hungary have remained low during the whole period. Even compared to the minimum and maximum load, PV output covers just 10–20% of the maximum load and approximately 30% of the minimum load.

Thus, PV utilization in EU is not following a South–North divergence as the solar resource potential would imply, but rather a West–East. Major PV market tendencies cannot be explained neither by the differences in the solar irradiation, nor by energy market integration or technology cost figures. Instead of physical-, technological- and resource-related specifications it is the financial aspect that drives the PV market, proving that the financial cost parameter is crucial.

2.1.1. FiTs and access to advantageous finance

The sudden upward policy cycle (Fig. 1, 2009–2012) was the result of risk mitigating Feed-in Tariff (FiT) schemes. When few MS introduced the FiT scheme following the successful German paradigm, the PV installation market started to boom. That was the case in several MS as soon as incentives were introduced (Spain, Italy, Greece, Czech Republic). However, when these policies changed the growth was diminished (2014–2016). The attractiveness of FiT scheme stems from its risk alleviation property; it offers the investor a stable lifetime cash flow and secures payback. However, the past -often sudden- changes of

FiTs' terms in EU have raised uncertainty [9] and discouraged investment.

NMS have faced a poor access to competitive financial sources, because FiTs appeared to be less effective in countries with high interest rates on loans. On the contrary countries where longer term loans with terms relevant to those of housing were available, SPVS flourished. The importance of this difference is vital in the solar field. Many financial analyses have shown that a 5% increase in the cost of debt can increase the share in the PV electricity costs between 18% and 45% [7,10,11]. The aforementioned discrepancy coupled with differences in electricity market prices, has hampered SPVS investment in the NMS. Hungary, the case study of the present research, is still far from reaching the RE target for 2020 (14.7%). In the past decade solar received limited attention among RES. However, even the plans for biomass, wind and also geothermal have only partially been realized.

2.2. Solar PV systems and land use issues

SPVS installations require substantial land resources, also depending on regional and technological conditions. Land occupation of ground-mounted SPVS may transform rural environments, where most often the solar farms are developed. Although there is evidence that SPVS transforms and occupy less land than other energy technologies [12], it alters rural landscapes practically unaltered for a long period. A significant impact of SPVS installation is the visual alteration of the landscape [13]. SPVS locations may also involve competition with agricultural activities and soil erosion [14]. As in many countries the land use changes induced by other RE technologies (mostly biofuel production and wind) have sensitised the issue, this became even more aggravated for the new greenfield PV developments [15].

2.3. Advantages of transforming closed landfills to solar PV systems

Installing SPVS on terrain primarily used for other income generation purposes is a practice that attracts increasing interest. This is particularly the case for utility-scale SPVS, that also offers the opportunity to restore and stabilize degraded land [16]. In our recent work, we have investigated the potential of SPVS installation on the face of existing dams [17] and over irrigation canals [18]. Closed landfills have particular advantages and site characteristics that favour efficient PV system installation. While offering a large, open space, they do not compete with agricultural or other productive uses. Moreover, due to their typical location far from environmentally protected areas (mountains, forests etc.), their transformation will not affect sensitive ecosystems.

Waste management facilities have an extensive road network that allowed waste transport from the surrounding areas to the landfill. Therefore, a PV system installation will be facilitated by the existing road network, enabling unobstructed and fast transport of the systems' equipment. Furthermore closed landfills are generally secured, fenced and monitored, which is also needed in solar PV systems. Having basic site monitoring and security already in place substantially reduces the relevant costs.

Closed landfills are often connected to the electricity grid through which they were electrified during their operating years. Connection can even have a significant capacity in cases landfill gas (LFG) electricity was produced. A planned closure of a landfill and the consequent reduction in LFG generation eventually leads to underutilization of the existing connection. Existing grid infrastructure is important for SPVS, especially if it has the capacity to transfer large quantities of produced electricity. Then the grid is accessible for the solar development with minimal intervention and cost, with landfill SPVS having advantageous connection cost compared to typical ground-mounted systems in greenfield land.

The proposed scheme could also be partially applied to landfills that have not fully ceased operation, providing further motivation for LFG

utilization. Waste deposition and the resulting LFG will produce electricity coupled with the one produced by the SPVS. Hybrid operation may result in a highly-efficient electricity production system [19]. Thus, while the solar PV system will generate electricity during the day, LFG engines will produce electricity when there is no sunlight. Electricity produced on landfill sites could cover multiple purposes within the site or its vicinity. Needs range from drainage water pumping, water treatment, LFG collection, monitoring and lighting.

2.4. Examples of solar landfill transformations

So far, SPVS on landfills have been pursued in the US and a small number in Italy, France, Germany and Korea. The only similar example in Hungary was built on lignite mine dump site.

The US are more advanced in the field of solar landfills, hosting completed landfill SPVS projects and having more in the planning stage. The earliest installation is the 276 kWp project in Paulsboro, NJ, that provides electricity locally to the site and operates since 2002. By 2012, 15 landfill SPVS projects were operating (total power capacity: 17.5 MWp) in New Jersey and an additional 27.5 MWp was located in other states [20]. Among these, the largest project is located in Nellis Air Force Base, NV; it was finalized in 2007 and has a power capacity of 13.2 MWp. The closed landfill provided 33 out of the total 140 acres of land that the SPVS project covers.

One of the early landfill projects outside US was built in Jeonju, a city in the Jeolla province of South Korea in early 2008. The project has a power capacity of 2 MWp and uses single-axis solar tracking.

In EU, there are few examples of SPVS sitting on brownfields. In late 2009 the Fito landfill in Manosque, France, was converted to a 4.1 MWp solar farm. The 54,600-panel project is the first of its kind in France, with more sites in Montpellier and Nante in planning phase [21]. In Germany the installation of a 800 kWp SPVS with 10400 modules started in 2009 in Kornharpen (Bochum) central landfill. In March 2011, the construction of the 1.9 MWp Heckfeld SPVS in South-West Germany was commenced. The 1.9 MWp solar park is sited on an old building rubble landfill and the total 23,640 solar modules are expected to generate 2 GWh of electricity every year [22]. Malagrotta former landfill in Rome, Italy, is one of Europe's largest landfills. Its total 1 MWp of solar power capacity is mostly (2/3) utilized through a flexible thin-film SPVS on a concrete layer that covers the landfill. The remaining capacity (1/3) is typical rooftop SPVS. The total installation covers an area of 5.3 acres and produces approximately 1.4 GWh annually [23,24]. In early 2017 the 5 MW project on the former Magtab landfill in Malta moved forward. This project replaced a wind farm project planned at the same closed landfill, rejected in 2015 due to its visual and ecological impact.

2.5. Assessment studies

As far as the solar landfill projects are concerned quite a few studies exist on the legal, technical and financial aspects but mostly on the experience from the USA and only rare information on some exploratory projects in the EU. In 1988, before the waste management regulations, the US hosted approximately 8000 landfills. By the year 2009 this number was dramatically reduced to 1900, providing thousand opportunities for sitting SPVS. US Environmental Protection Agency (EPA) analysed more than 1600 of them to estimate their RE potential [25]. The EPA in its *RE-Powering America's Land* project screened US landfills that deemed favourably for solar PV installations. More than 15 sites have been equipped with PV installations already, but many times more are in the planning or pre-feasibility phase. Transforming 10% of the identified sites' area to solar landfills, would result in more than 600 GWp of new renewable energy capacity in the US [26], which is the equivalent of the country's current gas capacity.

Recently, a study evaluated 54 near-closure landfills in California

[27]. The analysis focused further on 17 of them and revealed their potential generation of 3–4.5 GWh annually, the equivalent of 2% of the State's consumption. The US National Renewable Energy Laboratory (NREL) prepared detailed feasibility studies for two specific closed landfills in California, including an analysis of the projects' economic viability [28,29]. The two sites are very different in size with the first having a power potential of 27.5 MWp and the second 3.5 MWp (43 GWh and 5.2 GWh of annual production, respectively). Naturally, the estimated LCEO is lower at the bigger project and ranges between €11.9–13.25, while for the smaller one is €13.9–16.6. Considering that these studies used the module prices of 2013, it is expected that LCOE with the current 2017 prices would be significantly lower.

An analysis of 8 landfill sites in Gotland, Sweden showed a potential 22 GWh annual electricity production [30]. Despite the less favourable solar insolation, the projects' payback time was estimated at 10–12 years and the internal rate of return between 6.1% and 8.3%.

2.6. Advantages of installing PV on waste management sites

For the waste management side the main advantage of installing PV is that it links waste and energy and allows for an integrated management of both. Section 4.1.3 describes the twofold role of solar transformation that ensures water impermeability and produces electricity. This approach also enables attracting funds and benefits from other incentive schemes that would not otherwise be available for the landfill owners. As soon as a landfill seizes its operation, several costly procedures need to take place such as sealing the upper layer to obstruct rain water leach the ground water aquifer. However, incoming cash-flows that could cover these expenses have stopped. The installed PV system can provide additional finance as well as the electricity needed for pumping and LFG collection. The deteriorated area will also increase its value, however, monetizing this gain is complex and site-specific.

2.7. Scope of the present research and connection with existing literature

The present research aims to highlight the option of solar PV on closed landfills, that has not been sufficiently explored in the European context. This is a new approach and naturally there are few similar analyses published. The existing literature presented in Section 2.5 is mostly limited to techno-economic feasibility studies of solar landfills on specific locations. The present article, apart from presenting recent studies, also provides an overview of existing applications (Section 2.4). More important, it introduces a tailor-made methodology for site selection and capacity estimation in Section 3. The analysis also includes assessment of PV integration into the existing network.

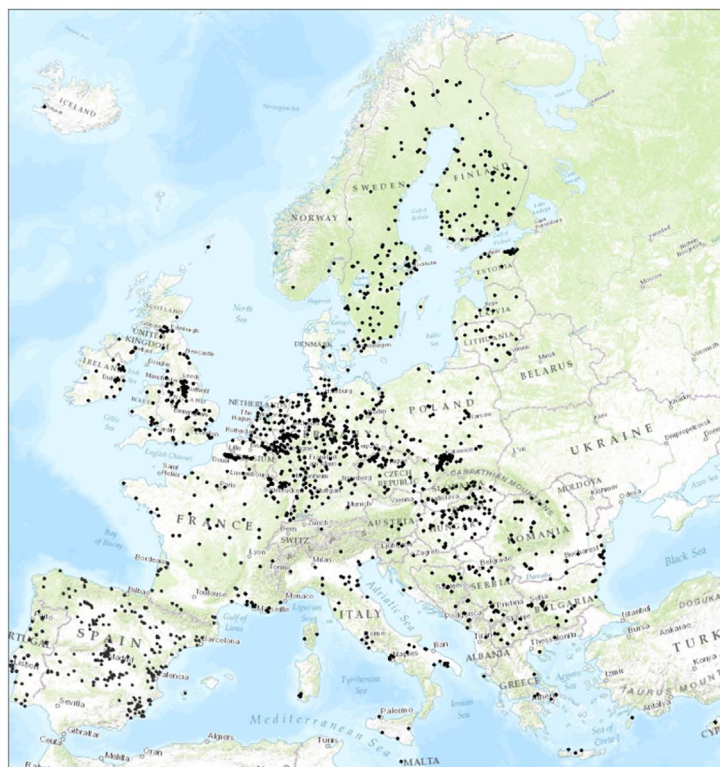
3. Materials

The methodology quantifies the potential of specific sites and acts as a guideline for mapping suitable, advantageous locations for landfill transformation. Its novel feature lies on the development of a GIS-based methodology that applies specific selection criteria for solar landfill development. The European land cover data and the landfill data set for UK and Hungary have been processed and analysed by spatial analyst applications developed for the study within the GIS software environment of the ESRI Arc/Info Workstation 9.3 and using the open source tools of Quantum GIS (QGIS 2.14.3). The final result (Fig. 4) was mapped by the cartographic elements built in ArcGIS Desktop 9.3.1.

3.1. Data collection and available information

Extracting landfill data from the harmonized European CORINE Land Cover (CLC) database has certain limitations. The CLC data sets

(a) Large European landfills.



(b) UK landfill data comparison

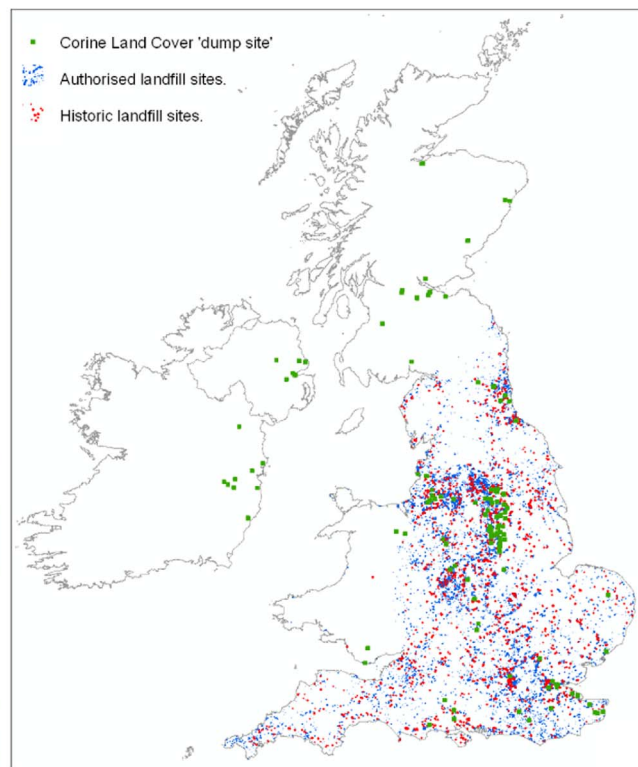


Fig. 2. European landfills. Source: authors' analysis on a) [31,33]; b) [31,32].

provide land cover information for the reference years of 2000, 2006, and 2012. Land cover types are classified in 44 classes, where the class of “dump sites” covers larger public, industrial or mine dump sites, which might include raw materials or liquid wastes [31]. The minimum mapping unit is 25 ha for areal phenomena and a minimum width of 100 m for linear phenomena. As the CLC data represents only larger, still operational landfills, excluding the relatively smaller sites, it provides a general snapshot of recent land cover of thousands of small historic EU landfills concerned. Although such sites have smaller area, and thus lower SPVS utilization potential, their particularly large number makes them an important under-developed asset, thus their analyses aiming resource assessment require more detailed spatial and descriptive landfill datasets involved.

Fig. 2a shows the European landfills (dump sites) as included in the CLC database. In order to estimate the number of potential locations of closed and recultivated landfills, the distribution of CLC dump sites has been compared with a landfill database for England [32]. It appeared that CLC contains only a fraction of the actually authorised landfill sites (see Fig. 2b). For England alone, the 1867 currently licensed landfills have a total area of 27,910 ha. CLC includes just 7380 ha of licensed, operating landfills for the whole UK. As far as historic dump sites are concerned, by processing the complete UK landfill database [33] we mapped 10,383 sites (47,569 ha) that seized operation during the last 50 years.

For our case study in Hungary, we collected detailed, up-to-date information from various sources. The developed data inventory provides information on historic landfills with descriptive data including geological and hydrological characteristics of the deposits, their operational status, environmental/human risks, level of recultivation and location, geodatabase on electric power transmission infrastructure, historic and recent aerial photos, digital elevation model, and legislations and policies should be followed in case of new installations. The different thematic datasets were then harmonized ensuring semantic integrity. In order to support geographical integrity, site

locations given as single points (in coordinates) for each location were visually compared to aerial imageries, and positions were corrected in case of mismatch. Further geoprocessing (e.g. transformation to unified spatial reference system, distance analysis from sub-stations, distance calculation from transmission lines in different voltage levels, distribution between national electricity providers, definition of surface characteristics based on high resolution digital elevation model) has been completed for all input data applied later in the developed GIS-based suitability model.

The data source for the Hungarian transmission network was the HM Zrínyi mapping and communications public service [34], digitized and corrected by the authors. Similarly, we corrected information on the substation network, provided by the Hungarian TSO [35]. A detailed dataset from the ENFO-project [36] was also validated and transformed to geodata to analyse the Hungarian municipal solid waste landfills. Similarly to the UK case, a gap appeared when comparing CLC information with the latter detailed data for Hungary. The detailed dataset includes 2568 historic landfills, with this number being ≈ 34 times higher than the one included in the CLC dataset ($n = 75$).

The detailed dataset contains description of 2568 Hungarian landfills with coordinates, size (overall volume: 180 million m^3 ; area: 30 million m^2), start and end date of operation. It also contains essential hydrogeological information on bottom layers and upper covers, water insulation measures and evidence on rain water infiltration and waste water leakage, mentioning also precipitation and groundwater patterns. Landfill ownership is also provided with municipalities being the dominant case. Moreover, a short description outlines landfill status and underlines potential hazards.

Most landfills have not been operational for a long period, with the majority shut-down in 1999–2000. Thus, even where compacting was not applied, waste settlement has been already completed, because it is typically completed in less than 10 years after closure. The following sections describe the required parameters selecting suitable locations for SPVS installation.

4. Methods: formulation of the two-tier multi-criteria analysis

Taking into account both the advantages and challenges of the proposed scheme, we developed a GIS-based decision support methodology that prioritizes suitable sites and estimates their capacity. It supports the utilization of landfills with advantageous characteristics (e.g. large unshaded area, hydrogeological conditions, terrain stability, current land cover, and transmission infrastructure proximity) for solar electricity production. Performance and reliability of solar landfills highly depend on the specific characteristics of each location. Proper selection involves lower investment expenditure, by utilizing existing infrastructure and reducing grid connection cost. Installation expenditures also decrease by selecting the appropriate PV technology that reduces scaffolding and fencing cost. The latter, along with careful selection of ground-stable areas, are also linked to the operational and maintenance cost. The criteria and methods used for the landfill site selection are presented in detail in the flowchart of Fig. 3.

4.1. First tier of multi-criteria analysis: suitable PV technology selection

The following sections give the detailed description of the first tier of multi-criteria analysis (MCA). The terrain stability and the method used for the landfill insulation are decisive factors in selecting the appropriate PV technology for each of the closed landfill sites. Based on our geodatabase, the first tier of the MCA classifies the closed landfill sites into the applicable PV technology options according to the method of waste compacting and to the type of upper landfill insulation.

4.1.1. Terrain stability

The waste compaction methods among the various types of waste require a case-by-case analysis (this was done by site surveyors in the Hungarian database). There is evidence in the literature that recently closed sites are more prone to settlement and soil instability [37]. Moreover, differential soil settlement might damage overlying struc-

tures with the foundation and the less flexible elements of the SPVS facing the risk of failure. For this reason, soil settlement needs to be evaluated as a primary input. Main waste compaction is produced by a landfill compaction vehicle with two main functions: to spread the waste evenly in layers over the landfill, and to compact waste to reduce its volume and help stabilize the landfill. For this study, the landfills were classified in three categories depending on the type of waste compacting applied with compactor (6 sites), typical compacting (1092), no compacting (1470) (see Table 1).

4.1.2. Water infiltration

Apart from ground stability, interventions must not interfere with the landfills' water impermeability. Closed landfills are typically covered by a geomembrane liner above which a 0.5–1.5 m encapsulating zone favours surface runoff and prevents rainwater infiltration that could potentially contaminate groundwater aquifers. This upper sealing zone supports surface runoff also through the creation of steep slopes that minimize water concentration. Moreover, it also prevents gas produced in the underlying decomposed waste to escape to atmosphere. This zone, as a rule, includes a covering layer, an insulating clay zone and is covered by an infiltration layer and grass. The landfills have been classified in 5 categories according to the upper-insulation method (see Table 1).

4.1.3. PV technology classification

Three PV technologies were selected to cover each of the 15 classes of compacting/upper-insulation classification: crystalline silicon PV with conventional mounting, crystalline silicon PV with lightweight mounting and flexible PV geomembrane. PV geomembrane technology combines flexible geomembrane and PV technology into a dual-purpose system to close the landfill and generate solar energy.

Table 1, illustrates the classification, where technology choice aims at maximizing the electricity output with the least-cost mounting, taking into consideration each site's constraints. While crystalline PV gives higher output on the same surface in given locations, it needs more robust supporting structure. Accordingly:

Sites with conventional waste compacting process are suitable to

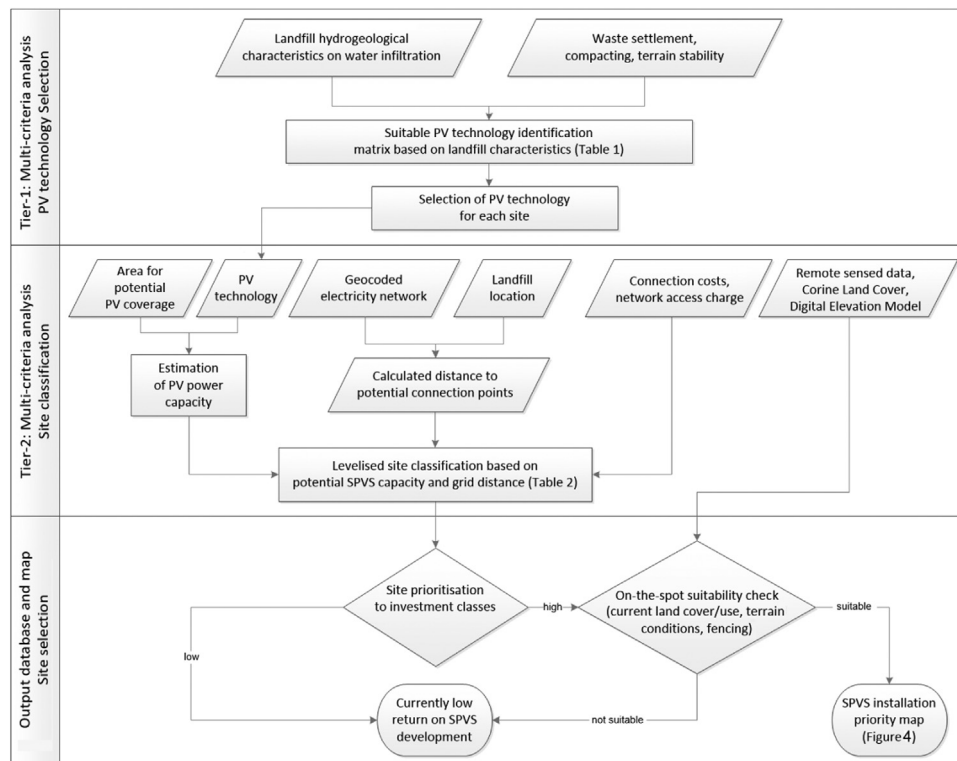


Fig. 3. Methodological algorithm of the developed two-tier multi-criteria analysis supporting the SPVS suitability mapping on closed landfills.

Table 1
PV Technology suitability matrix based on landfill characteristics.

Upper insulation	Compacting method		
	With compactor (6)	Typical compacting (1092)	No compacting (1470)
Clay (10)	Crystalline PV (c) (1)	Crystalline PV (c) (0)	Crystalline PV (l) (9)
Complete earth cover (455)	Crystalline PV (c) (2)	Crystalline PV (c) (136)	Crystalline PV (l) (317)
Combined membrane (2)	Crystalline PV (l) (0)	Crystalline PV (l) (0)	Crystalline PV (l) (2)
Thin earth cover (1271)	PV geomembrane (3)	PV geomembrane (479)	PV geomembrane (789)
No cover/not known (830)	PV geomembrane (0)	PV geomembrane (477)	PV geomembrane (353)

Harmonized colours with site identification in Fig. 4. Crystalline PV (c): conventional, Crystalline PV (l): lightweight mounting. The number of sites belonging to each group is indicated between brackets.

install conventional mounting structures of crystalline silicon SPVS. Leak-proof landfills are suitable for typical crystalline silicon SPVS, given that racks' installation does not require boreholes. SPVS systems' mounting must minimize interruptions of the upper zone, by minimizing the depth of excavations and the use of heavy machinery. Not penetrating the impermeable geomembrane during the construction is also required for projects' licensing.

Landfills with non-compacted waste may involve a more expensive lightweight mounting structure for the crystalline SPVS option.

For non-sealed and/or non-compacted landfills sites, the analysis examines the potential of solar PV geomembrane systems. The aim is to provide a twofold role i.e. water impermeability and electricity production. Despite having lower efficiency, PV geomembrane has multiple benefits for landfill installations: it can partially substitute a missing upper insulation layer and can be applied on steeper surfaces. Moreover, PV geomembrane is more resilient in differential settlement and applicable also on steeper surfaces.

4.2. Second tier: MCA for solar landfills suitability

Once the PV technology for each landfill site is selected (first MCA tier), the second MCA tier categorizes the landfills depending on two decisive parameters: the estimated PV power capacity that the landfill area can potentially accommodate (Section 4.2.1), and the distance from the landfill to the grid or to an existing electrical substation (Section 4.2.2). For the solar landfill categorization, the second tier of the MCA takes into consideration the connection cost rules of the Hungarian Energy Authority (Section 4.2.3) which distinguish connection fees by range of capacities (not by production figures) and distance to the existing grid.

4.2.1. Calculation of the applicable PV capacity

The selected PV technologies have different efficiencies: 17% for the commercialized crystalline and 10% for the thin film PV applied in geomembrane. The same landfill area can allocate different capacities depending on the selected technology (First tier, Section 4.1) and therefore could fall into different classes of applied connection fees (Section 4.2.3).

4.2.1.1. Crystalline silicon PV. Flat deck areas are the most suitable for crystalline PV installations. In these cases, the ground-mounted structure supports maximum utilization of the solar resource, by optimizing orientation and tilt angle. Naturally, the ground-mounted PV systems (conventional or lightweight, according to the local conditions) should be laid out to optimize land use and prevent panels shading one another (by minimizing the inter-row panels spacing to most efficiently utilize the available site). According to the International Finance Corporation Project Developers guidebook [38] the greenfield area required for 1 MWp crystalline silicon PVS is between 0.9 and 1.4 ha. Our analysis assumed a conservative limit on

landfills, therefore 1 MWp of crystalline PVS requires on average 1.5 ha, which is also in line with the information reported in [21–24,27–30,39]. This upper limit value takes into account the inter-row panel spacing, and as well the area used as perimeter clearance and—where applicable—landfill gas collection pipelines.

4.2.1.2. Thin-film geomembrane PV. In the case of PV geomembrane systems, slope orientation and crown height play an important role. Membranes are installed parallel to the terrain and the landfill geometry defines the degree of utilization of the solar potential. The quoted IFC study [38] calculates that 1 MWp thin film capacity covers 1.5–2 ha. Since, the membrane layers can be installed with no distance between them, geomembrane PV could achieve higher power capacity installation per unit of land compared to crystalline PV. However, landfill site experience [40,19] has shown that the associated capacities are smaller due to the lower thin-film efficiency and their installation being excluded from non-favourable landfill areas (e.g. North-facing slope). In order to take this particularity into account, we assumed a uniform utilization rate equal to 50%: accounting for the area occupied by the cabling and the service road and for the limitations of unfavourable slope conditions. A detailed surface-orientation geoanalysis was performed for the 10 largest landfill sites. The geoanalysis confirms that taking 50% as land suitable for thin-film installation is a conservative assumption: the area with favourable orientation was on the worst locations of 60%, but in most cases it was around 90%. Therefore, assuming only half of the landfill area is suitable for PV geomembrane, we constrained the capacity of PV geomembrane to 0.5 MWp/ha in contrast to the 0.75 MWp/ha for crystalline silicon SPVS.

4.2.2. Electricity network and substations' distribution

Existing power infrastructure is an additional important technical parameter. The integration of variable resources into existing energy systems is one of the major issues of PV development. Reaching a threshold capacity of the electricity generation portfolio can pose additional challenges to the system reserves and balancing policy. The grid integration part of the issue was taken into account in our methodology: landfills' proximity to electricity network and substations was also analysed. As the identified sites might contribute considerable amounts of power, it is essential to consider their integration to the existing power system and their connection to the grid. Proximity to the grid benefits the development of solar landfills and reduces the cost. Since the economics of the potential solar landfills is an important aspect of our MCA, proximity to potential connection points (from the geocoded electricity network) is a decisive parameter (see Section 3.1 for geocoded electricity network).

Table 2
Site classification based on potential SPVS capacity and grid/substation distance.

Level	Logical steps of classification*	# sites	Total MWp
1	$(CAP \geq 4)$ AND $(D_{SUBST} < 1000)$	2	18
2	$(0.5 < CAP < 50)$ AND $(D_{HV} < 500)$ OR $(D_{MV} < 500)$	93	164
3	$(CAP > 0.5)$ AND $(500 < D_{MV} < 3000)$ OR $(CAP > 4)$ AND $(500 < D_{HV} < 5000)$	80	169
4	$(CAP \geq 0.5)$ AND $(D_{MV} > 500)$ AND $(D_{MV} < 3000)$ OR $(2 < CAP < 4)$ AND $(500 < D_{HV} < 5000)$	23	63
5	$(0.25 < CAP < 0.5)$ AND $(D_{LV} < 50)$	13	4
6	$(0.25 < CAP < 0.5)$ AND $(D_{LV} < 150)$	31	11
7	$(0.003 < CAP < 0.25)$ AND $(D_{LV} < 50)$	89	7

Variables: CAP – estimated power capacity in [MWp], D_{SUBST} – distance from the nearest substation, D_{HV} , D_{MV} , D_{LV} – distance from the high, medium, low voltage network, respectively [m].

4.2.3. Grid access, costs, licensing and planning

As the size of the proposed PV systems is relatively small compared to other power producers, high connection fees can become prohibitive for PV development. With the increase of renewable energies in the electricity portfolio the grid integration of PV in the existing national grid has become a major issue in meeting the RE targets in EU Member States. Distribution System Operators (DSOs) are responsible for the operation and maintenance of the low (LV) and medium voltage (MV) network (<120 kV), and therefore they are the main responsible parties for dealing with the grid access process of Renewable Energy Sources (RES) producers.

4.2.3.1. Connection fees and grid extension costs in Hungary. High voltage (HV) network (above 120 kV) development follows a regular planning procedure: the Hungarian Transmission System Operator prepares medium- and long-term plans that are subject to approval by the Hungarian Energy Authority (HEPURA) and are available online for public consultation. Information of HV lines operated by DSOs are available offering updated information on the HV developments. Medium and low voltage (MV and LV) network plans do not pass through HEPURA, and therefore access to updated information is more difficult. The connection fees to the grid are:

- HV network: €11.000/MVA
- MV network: €120–150/kVA, depending on substation's voltage
- LV network: €40/VA

The connection cost also depends on distance; if the required new line length exceeds:

- 500–250 m for MV (air/underground cable)
- 50–20 m for LV (then power producers cover the cost.)
- 30–15 m for LV (in the property's boundaries. Then power producers cover the cost.)

4.2.3.2. Connection and licence fees for RES in Hungary. Grid regulation prioritizes RES by providing priority connection and reduced fees. The Hungarian Energy Authority (HEPURA) requires a preliminary connection agreement between the RES producer and the grid operator as a precondition to obtain the licence for grid access. Two legislative items [41,42] include detailed technical and financial conditions and provide a priority grid connection to RES producers. In case the new RES power plant connection requires a network upgrade, RES developers need to cover the additional cost.

Under the HEPURA rules, RES power plants with capacity between

0.5 MW and 50 MW are entitled for a simplified licensing procedure. They receive the construction and operation licence as a single licence from HEPURA. The licensing fee is differentiated according to the size of the power plant €11/kWp to €0.54/kWp (from €5.500 to €27.000). Although PV plants enjoy these RES benefits, DSOs have limited tools to speed up connection works.

4.2.4. Site classification based on prioritizing least-cost options

The solar landfill categorization has taken as a base the connection and licence cost rules of HEPURA, since connection and licence fees depend by the range of installed capacities and distance from existing grid infrastructure. It is clearly visible that relatively larger RES projects can have proportionally lower connection fees with the distance from existing lines also playing an important role in the system cost. The selected landfill sites ($n = 331$) were ranked in 7 priority levels depending on the parameters distance from grid (or electrical substation) and PV power capacity. The ranges of each level are presented in detail in Table 2.

The allowed distance to HV line depends on the HEPURA approval: the analysis calculated with HV line >5 km or distance to substation >1 km for the larger best locations. Setting limits on maximum distance from the grid (see Section 4.2.2) and on minimum potential (PV power capacity <250 kWp), excluded around 80% of the landfill sites either for having too small potential and/or being too far from the grid, and thus requiring heavy investment on grid extension.

The combination of RES plants entitled for a simplified licensing (PV capacity between 0.5 and 50 MW) and the higher connection cost for distance larger than 500 m for MV and HV lines distinguishes the classification of levels 2–4. Our classification includes also levels 5–7 with smaller capacity potentials as these sites are considerably large in the PV market.

The 331 identified landfills have advantageous site characteristics providing opportunities for cost-efficient PV system installation. They offer a large, open space which favours PV electricity production. They do not compete with agricultural or other productive uses. Moreover, due to their typical location far from environmentally protected areas (mountains, forests etc.) the effect of shading on PV panels from the surrounding is not expected to be significant.

5. Results

The presented GIS-based ranking methodology provides policy makers the possibility to focus their efforts in simultaneously implementing environmental protection, waste management and clean energy related objectives.

5.1. Reaching threshold capacity of the electricity generation portfolio: integration issue

In most EU Member States grid integration issues of variable renewable energy sources has become the major issue meeting the renewable energy targets. Complementing different RE sources has been a cost efficient option to reduce these grid integration costs [43]. The Hungarian grid operators' report [41] calculates that 56% of the additional system balancing cost is due to wind and this is insignificant for the PV. The latest energy policy changes in Hungary [42,44,45] show that, instead of new wind energy installations, PV could be a cost-efficient RE option. In this study we identified a low-cost complementing RE power, large solar landfill options that can complement the existing variable sources. They are all in the proximity (distances defined by the grid integration HEPURA code) of the existing network, they are equally spread over the country (unlike the North-Eastern dominance of the wind turbines) and relatively close to the load centres. The overall identified SPVS potential in the closed landfills of Hungary has power capacity potential of 450 MWp. This figure is almost 50% higher than the wind capacities currently installed in the

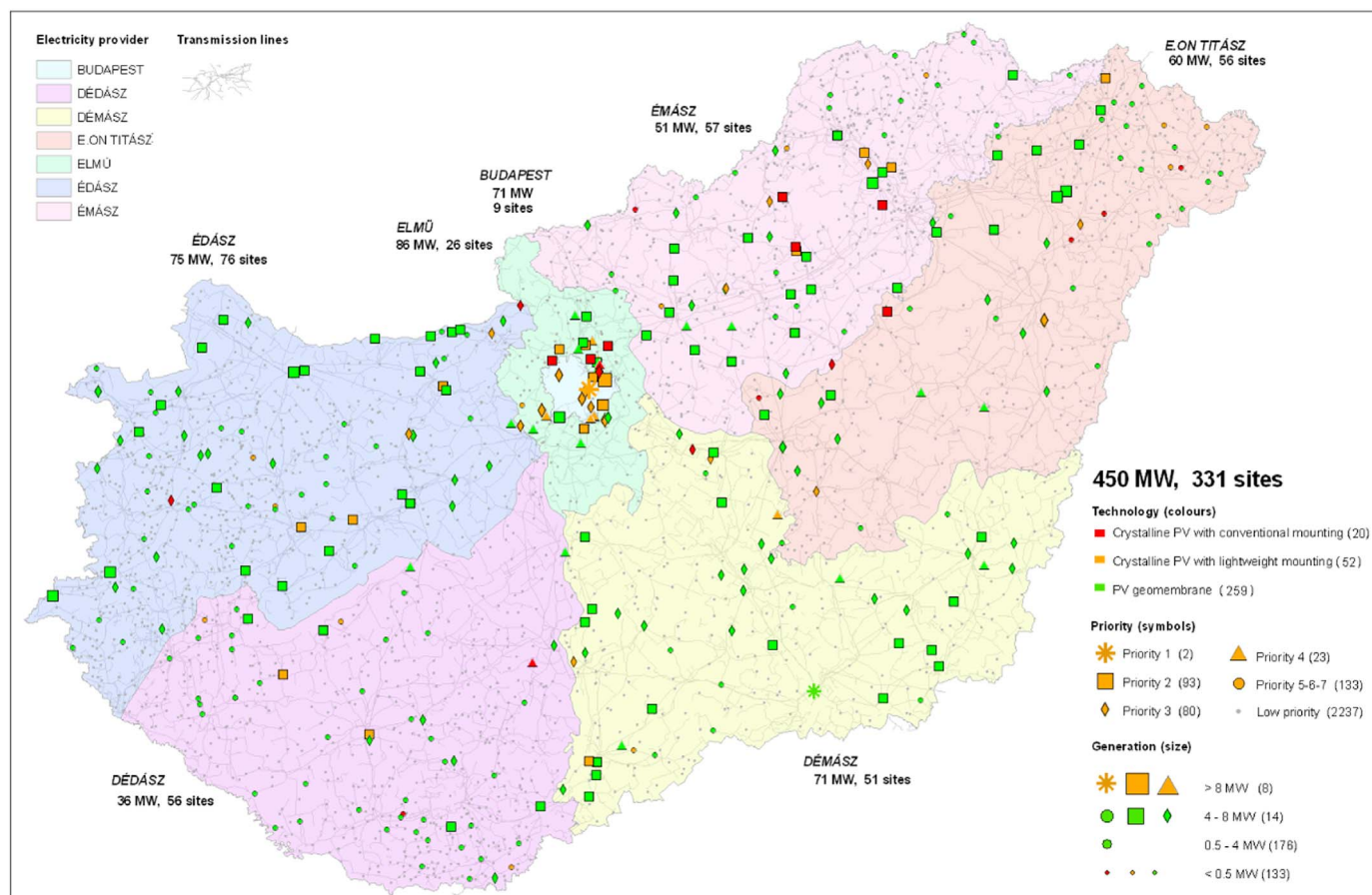


Fig. 4. Characteristics of the identified sites in different regions. Site colour identifies the technology classification; symbol identifies the least-cost priority classification and size symbol the potential power capacity for each site.

country. Despite the fact that almost 2000 smaller landfills out of the total 2568 sites are excluded from SPVS utilization, the remaining sites utilize two thirds of the theoretical potential available in the total 3000-hectare landfill area.

5.2. Mapping, identification and classification of solar landfills

The identified sites are shown in Fig. 4. Different symbols are used to distinguish their 7 classes, as described in Table 2. The size of each symbol is proportional to the available potential power capacity (see description in the legend of Fig. 4).

The methodology ranked two sites with 13 and 5 MWp capacity (the first one with a lightweight mounting and the other adopting geomembrane technology) in the first category as they are not only large, but are also located close to a sub-station. Therefore, they are ideal locations for power system connection. They are also located in the vicinity of big cities (Budapest and Szeged) as shown in Fig. 4 with the star symbol. The following two priorities contain 173 sites, with a total proposed capacity of 333 MWp. These sites are close to the medium voltage lines and are entitled to preferential connection charges. The remaining 156 sites (84 MWp in total) are relatively smaller PV systems, which would connect to the nearby low voltage network.

It appears that the majority of the selected landfill sites, near 80%, are proposed with geomembrane technology. This is followed by a smaller share of sites with lightweight ($n = 52$) and conventional mounting ($n = 20$) crystalline PV systems. In these sites a certain form of compacting has already been carried out during their operation (see detailed distribution in Fig. 5).

In the case of 258 sites no upper sealing has been applied, or they

were simply covered with a thin earth layer. For these sites geomembrane PV system is more suitable in order to provide waterproofing. The remaining >2000 sites are generally too small and relatively far from the grid. Accordingly, they are characterised as not suitable for solar PV system utilization.

The geographic distribution of the identified projects is very balanced. All regions, and the respective electricity providers, have a power potential that ranges between 50 and 90 MWp (except the South-West region with 36 MWp, which is a region characterised by small-sized settlements). The highest potential is available at South-East Hungary, belonging to the electricity provider D m sz. This region is also characterised by the highest amount of solar irradiation in Hungary [46]. It is interesting to note that the larger sites are close to large load centres (main cities), since old landfills were naturally located close to waste production hubs. Utilization of the bigger sites in the North-West would coincide with existing concentrated wind capacities. Installing SPVS of similar magnitude near existing wind capacities could be beneficial from grid integration aspect, as these intermittent resources often complement each other to a considerable extent [47].

6. Discussion—conclusions

6.1. Win–Win solution

The proposed combination of landfill and solar PV installations exploits the synergies between waste and energy management offering a win-win solution (see the first large scale application in Hungary in Fig. 6). The developed methodology geoanalyses existing sites, suggests the appropriate PV technology for each site and finally the landfill sites

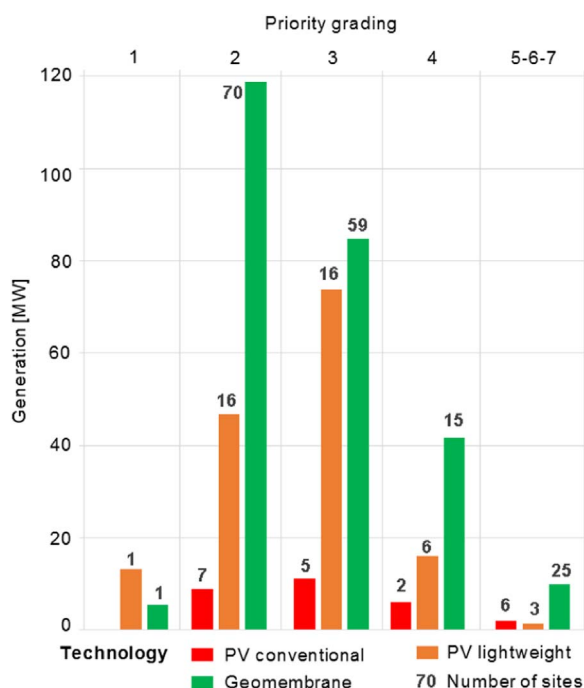


Fig. 5. Distribution, capacities and technologies in the identified priority classes of selected closed landfills.

are hierarchically classified. The methodology has been applied in Hungary to quantify the potential of the closed landfills sites.

From an economic perspective, areas in the vicinity of closed landfills are unattractive for real estate development with the value of land and housing decreasing. So far reclamation of such landfills is the main path to increase the land value and attract investors. Although contamination has been capped in re-cultivated landfills, the demand for real estate uses is simply non-existent. Recovery of closed landfills and risk mitigation is a long process that diminishes the number of options for landfills' utilization. Transforming closed landfills to SPVS provides numerous benefits and generates multiple efficiencies and cost-saving opportunities. Moreover, the magnitude of the electricity generation potential for the employed land would increase the economic value of depreciated lands with the additional advantage of not occupying green-field areas.

Parallel to that, the local authorities have the opportunity to solve a long-lasting, chronic problem that adversely affects property prices. A systematic initiative has the potential to attract development financing. Local initiative for city-level plans, like the successful Covenant of Mayors initiative [48], could reinforce this type of planning. As many of the landfills are owned by local authorities, the generated electricity will constitute an important element of the local long-term energy planning. The presented industrial symbiosis is an example of the approaches needed to facilitate improved urban resource management [49]. Solar landfills will be important contributors to municipalities that have set targets for energy efficiency and increased share of RES in



Fig. 6. The 18 MW solar park next to the lignite power plant of Visonta, Hungary.

their “Sustainable Energy Action Plans” of the Covenant of Mayors [48]. The benefits for the municipalities will be multiple: mitigation of an environmental hazard, increase of property value as well as an increase of the share of the local clean energy portfolio. Governmental additional finance, incentives and tax exemptions will support the economic feasibility of the projects and support economic growth and job creation.

The advantage of modular PV technology may play a more pronounced role in bridging the gap between targets and implementation. The proposed PV capacities complementing the existing wind generation could play a major role in decreasing the RE integration costs: their combination would decrease the necessary reserve margins in the power system. In a subsidy-free environment the cost-effectiveness of the applied solution plays an important role in market development. Involving the community and building consensus are needed to overcome barriers to brownfield energy transformation. “Social licence to operate” is a methodology that has already been successfully applied to the wind and geothermal sectors [50]. Adopting a similar strategy to promote solar landfills could increase citizens' acceptance and support an effective, simplified permission procedure.

6.2. Outlook and limitations for implementation of solar landfills

Licensing solar landfills is a potential challenge that depends on national legislation. Some countries and local authorities require specific building permit to install ground-mounted systems. Most of existing regulations requires closed landfills to get special permission for SPVS installation given their characterization as hazardous sites.

An additional challenge is related to the selection of mounting system. Landfills' special conditions impose specific restrictions on ground penetration. Moreover, the risk of ground differential settlement needs to be taken into account. The current literature lacks a comprehensive analysis of alternative racking systems for SPVS on closed landfills. It is important to assess the geotechnical effects of the SPVS to the landfills' surface [51]. Ballasted mounting systems are a suitable option, since their non-invasive racking does not require ground penetration. Moreover, SPVS mounted on ballasted rack are lighter and minimize the impact to ground's integrity. Driven pile mounting systems can result to an even lighter construction that does not rupture the waste layers nor release underlying contaminants [52,51]. Tracking mounting system adds extra weight and are less suitable for landfill SPVS. Weight is also an important parameter for choosing PV modules, with thin film modules being advantageous compared to crystalline silicon modules.

6.3. Enhancing the solar landfill georeferenced tool at local and EU level

Site specific surveys could increase the accuracy of our estimated capacities and technology choices. The presented georeferenced analysis could form a basis to develop a bottom-up initiative at municipal-level. Still, the implementation of each identified project would need to be preceded by case-by-case feasibility study.

As already mentioned, the CLC dataset contains information only for large landfills at European level. In the case of Hungary, where landfill information is fragmented, CLC provided information about only 3% of the sites. The quantity of landfilled waste produced at EU level [1] derives to a general figure on the overall EU landfill available for installation of SPVS. As the present study focuses on closed landfills, we considered the waste stream between 1995 and 2000. Based on the 1.5 ha/MWp approximation, 13 GWp of SPVS could be installed on the closed landfill sites in the territory of the European Union, a capacity similar to total annual PV installation during the three peak years (2010–2012). In the case that georeferenced information on former waste disposal sites becomes available at MS level, a similar analysis can be performed for any MS. As many countries

received funding for closing landfills according to the European legislation, these site specific information can be available in the technical assistance coordination bodies of the MS.

7. Disclaimer

The views expressed in this paper are purely those of the authors and may not in any circumstances be regarded as stating an official position of the European Commission.

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