Development of a Comprehensive Pavement Design System for Roads in Wind and Solar Farms

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Abstract

This paper briefly, illustrates the structure and contents of an ongoing research program aimed at developing a set of procedures and tools to be used for the design of pavements in renewable energy projects and mainly in wind and solar farms. Challenges related to this topic derive from the non-standard nature of several factors that affect the structural and functional performance of such pavements, with the consequent need of employing purposely defined prediction methods, design criteria and specifications. Further crucial aspects to be taken in account in the research program are related to the life cycle cost analysis of pavements, to be carried out in a multinational context by considering alternative scenarios according to an OPEX (operating expense) versus CAPEX (capital expenditure) philosophy. It is envisioned that results and deliverables of the project will contribute to the enhancement of the effectiveness of operations in wind and solar farms, optimizing investments and leading to the selection of more sustainable pavement solutions.

Keywords: Renewable energy; Wind and solar farms; Pavement design; Performance prediction; OPEX versus CAPEX; Experimental tests; Sustainability

1 Introduction

ENEL Green Power S.P.A. (hereafter indicated as “EGP”) is a Company of the Italian utility group ENEL S.P.A. that develops and manages power generated from renewable resources worldwide. It is currently in charge of more than 1,200 power plants located in five continents, with assets in operation or under construction in 21 Countries. The overall worldwide energy capacity of EGP plants, either in operation or under construction, is of the order of 56 GW, deriving from a mix of renewable resources, which include wind (yielding approximately 33% of total capacity), solar (21%), hydroelectric (45%), geothermal(1.4%) and biomass (0.1%).

In view of the impressive data indicated above, EGP can be considered one of the major private international players that are operating and investing resources in the global green energy transition, which will be crucial to react against ongoing climate change for a more sustainable future.

As part of its efforts to improve the effectiveness of its investments and operations, since its foundation EGP has been constantly supporting research activities both of the fundamental and applied type in multiple areas of engineering and earth science. In such a context, in 2021 it secured appropriate resources for the development of a comprehensive pavement design system for roads in wind and solar farms. Following a competitive bid that involved the participation of several invited research institutions specialized in the area of pavement engineering, the research contract was awarded to the Politecnico di Torino, Italy. Activities were commenced in April 2022 and are expected to be completed by the end of 2023.

This paper briefly describes motivation, structure and contents of the abovementioned research program, with a synthetic illustration of specific challenges, inherent complexities, adopted approaches and expected deliverables.

2 Motivation

The need for a comprehensive research program focused on pavement design for wind and solar farms originated from the status of engineering operations managed by EGP worldwide, in which critical issues were identified. As described in the following, such issues are related both to the structural evaluation of pavement solutions and to the analysis of corresponding cost.

According to current practice, pavement design activities for each farm are carried out by Consultants designated by Contractors. Employed design procedures, such as the AASHTO 1993 method, are usually quite empirical and conservative, originally developed for standard roads and highways and lacking the possibility of taking in account the peculiar factors that characterize pavements to be constructed in wind and solar farms. These include non-standard and exceptionally high vehicle loadings, extreme climatic conditions, poor sub grade bearing capacity, and limited availability of high-quality materials. Further challenges that arise in the use of standard empirical methods stem from the need of implementing strengthening techniques, often unique to certain Countries, and of employing locally available recycled materials. Finally, complexity of design operations also derives from the need of differentiating pavement cross-section's as a function of the hierarchy and expected use of the different branches that compose the vast mobility network of a given farm. In such a context, it should be considered that these sites might have a remarkable land footprint, covering rural areas with an extension that for a reference energy capacity of 100 MW can be, depending upon the specific technology, of the order of 50-100 hectares for wind farms and of 150-250 hectares for solar farms. Corresponding infrastructures for internal mobility can form networks characterized by a significant extension, which in the worst-case scenario are constructed on uneven and steep terrain with potential ground instability.

While considering current practice followed by Consultants in design operations, it was also observed that unfortunately structural design evaluations are seldom combined with analyses related to construction or life cycle costs, thereby preventing the true optimization of investments. Such a limitation needs to be overcome in the research program by defining a sound assessment procedure that includes alternative scenarios according to an OPEX (operating expense) versus CAPEX (capital expenditure) philosophy. In turn, these should be translated in operative plans that may entail, depending upon the case, stage construction, planned maintenance and scheduled rehabilitation. The ultimate goal of part of the program is to create guidelines to be implemented at the multinational level, thereby ensuring the consistency of choices made worldwide by designers and decision-makers.

3 Structure and Contents

The research program is structured in multiple interconnected tasks, conceived to yield deliverables that will be shared with Consultants, Contractors and EGP Technical Departments worldwide, with the added value of being reference milestones for future research activities. Further refinements of the scope and contents of each task may occur in the future phases of development as a function of achieved results.

3.1 Technical and Scientific Background

The technical and scientific background of the research program was defined in Task 01, already completed at the time of preparation of this paper, which consisted in a bibliographical study carried out by thoroughly analysing international literature. Task outcomes were synthesised in a report (Politecnico di Torino, 2022) that contained a general description of infrastructures and pavements, a synthesis of the most common pavement design procedures, a review of technical information on component materials and layers, and a discussion of financial and environmental aspects. Contents of this report constitute the reference baseline for many of the other tasks included in the project.

Given the scarcity of published documents focusing on pavements for wind and solar farms, literature analysis considered low-volume roads (LVRs) satisfying the mobility needs of local communities in rural areas, together with function-specific roads (FSRs) designed and constructed to serve the industry or to allow access to remote areas (such as mining haul roads, agricultural roads and forestry roads) Pretoria Department of Transport, (1990); Tannant & Regensburg, (2001); Thompson et al., (2019). In these contexts, it was recorded that studies and specifications generally refer either to "paved roads", that entail the presence of flexible asphalt pavements and rigid concrete pavements, or to "unpaved roads", which can be further divided into the categories of gravel roads, driving surface aggregate (DSA) roads and earth roads. Additionally, it was noted that unpaved roads can be either unsealed or, in particular cases, sealed (by means of bituminous or non-bituminous surface treatments). Typical distresses were identified for all pavement types, highlighting their origin and their implications on structural and functional performance (FHWA, 2003, 2015). Finally, pavement selection criteria were discussed, showing that they can be generally expressed by referring to average daily traffic (ADT) or annual average daily traffic (AADT) (Pasindu et al., 2020).

With respect to pavement design procedures, the literature review synthesized the principles and procedures more appropriate for pavement design of paved and unpaved roads. It was noted that while methods of the former group (such as AASHTO 1993 and those with a mechanistic framework) are well known to pavement engineers, those belonging to the latter group (such as those developed in Australia, Canada, Russia and South Africa) are more familiar to LVR and FSR specialists.

Technical information on basic and mechanical characteristics of materials were collected by focusing on aggregates used in unbound layers (including those derived from recycling), mechanically and chemically stabilized soils, and geo synthetics. Whenever relevant, mechanical modelling methods, selection criteria and design principles were also reviewed.

Finally, Task 01 addressed the themes of costs and environmental impact by introducing the basics of Life-Cycle Cost Analysis (LCCA) and Life Cycle Analysis (LCA). Preferred analysis approaches were highlighted, together with guidelines to be followed for interpretation of results.

3.2 Review of Current Practice

Review of current practice in the design of EGP projects was carried out in Task 02 of the research program, close to completion at the time of submission of this paper in which available pavement-related design documents of EGP wind and solar farms, in operation or in construction throughout the world, were analysed in detail. The ultimate goals of such a review were to identify existing conceptual gaps and inconsistencies, and to perform a comparative evaluation of the various pavement cross-sections by employing a common approach for the assessment of expected design life and construction costs. Outcomes of these analyses were synthesized in a specific report (Politecnico di Torino, 2023a) that will be further integrated towards the end of the research program by making use of more advanced design concepts and more comprehensive financial evaluation methods in accordance with the work developed as part of Tasks 03 and 04.

It was observed that although design Consultants in most part make use of the AASHTO 1993 method, non-negligible inconsistencies exist with respect to the procedures followed, for both paved and unpaved roads, to compute (or assume) several input data. These are related to extraction of bearing capacity data from geological and geotechnical surveys (expressed in terms of CBR index and thereafter converted into resilient modulus), to the inclusion of seasonal effects that can account for changes of water content in the sub grade and unbound layers, to the assumption of meaningful layer coefficients for standard and non-standard materials, to the calculation of the number of Equivalent Single Axle Loadings (ESALs) in the design period, to the assignment of representative ESALs to different branches composing the network of transportation infrastructures (both temporary and permanent), and to the identification of acceptable serviceability at the end of the design life. Furthermore, it was confirmed that design Consultants seldom referred to stage construction or planned rehabilitation options, with a very limited attention to financial implication of their choices and with no formal value engineering assessment.

Based on the review outcomes synthesized above, in Task 02 comparative analyses were carried out, for a selected number of representative EGP projects, by applying the AASHTO 1993 procedure in a uniform and consistent way, thus amending previous design choices according to a common rationale. Special attention was reserved to design ESALs, that were expected to show a relationship with extension of farms, length of the infrastructure network and total energy capacity. Further calculations were made by hypothesizing alternative scenarios based on terminal serviceability changes and introduction of stage construction. Construction and life cycle costs were computed for all considered cases, thereby leading to the preliminary identification of preferred general design strategies. It was concluded that in the absence of strict guidelines on the use of the AASHTO 1993 procedure, the likelihood of significantly overdesigning or under designing pavements has been extremely high, with the consequent waste of financial resources due to excessive expenses for construction (in the case of overdesign) or for early maintenance and rehabilitation (in the case of under design). As a consequence, while still working on the development and implementation of improved pavement design methods, clear guidelines on the use of AASHTO 1993 will be shared by EGP with design Consultants and Contractors.

3.3 Development of Pavement Design Procedures

By taking in account the outcomes and conclusions of Task 02, specific pavement design procedures were purposely developed as part of Task 03, currently in its finalization stage (Politecnico di Torino, 2023b). These procedures present the distinctive character of including a sound mechanistic component based on the analysis of the results of specific experimental tests and environmental modelling activities, to be performed in the preliminary phases of site assessment, and to the evaluation of stresses and strains induced in pavement structures by vehicle loadings.

According to the philosophy adopted by the research team during their development, such procedures will yield results characterized by a higher reliability in comparison to empirical ones (such as AASHTO, 1993) but will also allow significant life cycle savings since the likelihood of overdesign or under design will be reduced.

The new procedures were developed for both paved and unpaved roads, although in the former case the main focus was on asphalt pavements since in wind and solar farms rigid structures are exclusively used in pads and platforms or to overcome high gradients of the road alignment in critical locations. Damage mechanisms and their relevance to pavements in wind and solar farms were highlighted for the most frequently occurring categories of distresses (cracking, distortion and disintegration for paved roads; surface defects and structural defects in the case of unpaved roads) (FHWA, 2003; Paterson, 1991). Corresponding design evaluations were introduced in the form of analytical (transfer) functions and specific calculation procedures AASHTO, (2008); Austroads, (2017); La Vern, (2016); NCHRP, (2002); SRSMT, (2001); (Yapp et al., 1991) that constituted the backbone of the proposed methods. Appropriate guidance was provided with respect to the assessment of traffic loadings in the design life and climatic conditions, and the steps to be followed for design verification (possibly to be carried out iteratively until reaching optimization) were clearly illustrated. Details of the procedures will be shared in the near future with the international technical and scientific community according to EGP policies.

3.4 Improved Use of Pavement Design Methods and User-Friendly Implementation

In order to make the best possible use of the pavement design procedures developed as part of Task 03, EGP requested to include in the research program specific tasks dedicated to the definition of guidelines for their improved use in adherence to the OPEX versus CAPEX philosophy (Task 04), to the creation of user-friendly software-based tools for their implementation into practice (Task 05), and to the formalization of a simple pavement design catalogue to be employed for budgeting purposes, in preliminary design, and in standard projects of limited importance (Task 06). Activities of these tasks are still in progress and related deliverables are expected to be finalized by the end of the second quarter of 2023.

3.5 Experimental Testing and Technical Specifications

As per the requirements set by EGP, it was planned that activities related to the development of pavement design procedures and tools (comprised in Tasks 03 to 06) would be supported by experimental investigations (Task 07) and by the review and update of existing EGP technical specifications (Task 08).These activities were commenced in the early stages of the program and will continue throughout its development until the end of 2023.

At the time of submission of this paper, activities of Task 07 have been exclusively carried out in the laboratory, mainly focusing on the physical and mechanical properties of sub grade soils and unbound and cement-treated materials for sub-bases and bases. Emphasis has been given to the assessment of the resilient modulus of granular materials by means of triaxial tests, exploring the full load spreading potential of these materials by operating on samples prepared with variable degrees of water saturation (representative of different climatic conditions and/or seasons) and of compaction level (representative of the variable effectiveness of construction operations). Relevant models are being fitted to experimental data to take in account their non-linearity in subsequent pavement design calculations. Samples currently being analysed were taken from two EGP farms (one wind and one solar project) and in two additional reference sites.

Review of technical specifications (EGP, 2021, 2022a, 2022b) is being performed in Task 08 by referring to international literature and past experience of the research team in similar projects. Furthermore, ongoing updates are taking in account the results achieved in the other tasks of the program (including Task 07) in order to ensure full consistency and completeness to the entire set of deliverables. Details of the contents of these improved specifications will be shared with the international technical and scientific community according to EGP policies.

4 Conclusions

At the time of submission of this paper, limited conclusions can be drawn from the work performed in the described research program since it is at less than 50% completion. Nevertheless, finalized and ongoing activities yielded interesting results that confirmed the relevance of addressed topics. Thus, it is envisioned that deliverables of the project will contribute to the enhancement of the effectiveness of operations in EGP wind and solar farms, optimizing investments and leading to the selection of more sustainable pavement solutions.

Further activities on the subject of pavements in wind and solar farms are being planned to validate the results coming from the ongoing research program. These will be part of a follow-up program that will include, but will not be limited to, full-scale validation of predicted pavement performance, implementation of emerging technologies in pavement construction operations, closed-loop recycling of materials in wind and solar farms, and development of tailored LCA models.

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