

Article

Expert Support System for Calculating the Cost-Effectiveness of Constructing a Sewage Sludge Solar Drying Facility

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Abstract

Sewage sludge, as a by-product of wastewater treatment, represents a significant cost factor in the operation of wastewater treatment plants and accounts for up to 50% of total costs. As sewage sludge still contains a high proportion of water after the basic treatment processes (thickening, stabilization and dewatering), sludge drying helps to reduce further treatment and disposal costs. Conventional drying methods are associated with high energy consumption, making solar drying a more cost-effective alternative. This paper analyzes the economic aspects of constructing a sewage sludge solar drying facility with the help of an expert system based on neural networks. The system considers a range of parameters (plant capacity, transport distance, transport and treatment costs, etc.) to assess the values of the investment as well as the operation and maintenance costs. The analysis was carried out using NeuralTools (Lumivero). Two main options for sludge disposal were investigated: treatment at a regional center (with the sub-options of own or outsourced transport) and handing over of sludge to another legal entity. In total, five neural network models were developed based on the input load (from 75 to 10,000 t/year and from 10,000 to 20,000 t/year) and transport method (own or outsourced transport), resulting in an analysis of over 670,000 scenarios. The key output variable was the net present value of costs over a 30-year period. The results demonstrated high model accuracy (error < 5%) and allowed a comparison of the profitability of constructing a sewage sludge solar drying facility with alternative methods of sludge disposal, in particular with the transport and disposal of the dewatered sludge.

Keywords: dewatered sewage sludge; dried sewage sludge; solar drying; neural networks; expert system; net present value



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1. Introduction

Sewage sludge (SS) management is an essential component of a comprehensive wastewater management system. From the very beginning of wastewater treatment system development, SS handling has posed a fundamental challenge. With the growth of urban areas, an increasing number of people connected to public sewage systems, and the increasing stringency of regulatory requirements regarding SS disposal, the complexity of this issue has intensified even further. In recent decades, the challenges associated with efficient, environmentally friendly and cost-effective SS management have become even more prominent, with final treatment and disposal emerging as key areas of interest within the water management sector.

Raw SS, produced through the wastewater treatment process, is a very viscous mixture of water and solid matter (Figure 1). Immediately after treatment, the dry matter content in SS is only about 1–2%. Water makes up the largest portion of raw SS and can be categorized as follows [1]:

1. Free water that is not bound to sludge particles;
2. “Interstitial” water trapped between sludge particles;
3. Capillary (surface) water surrounding solid sludge particles;
4. Intracellular and chemically bound water.

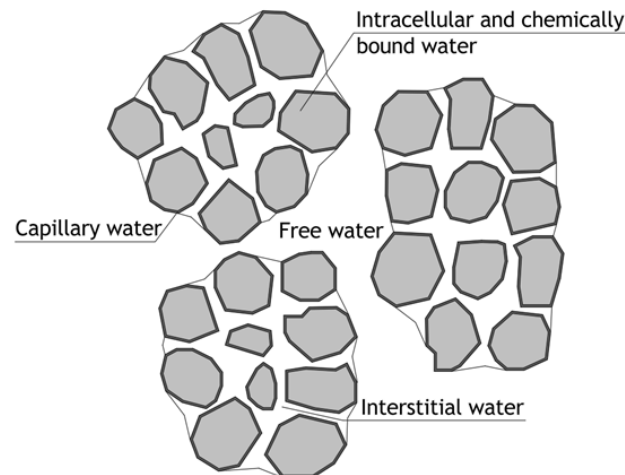


Figure 1. Water distribution in raw SS.

The basic SS treatment processes at most wastewater treatment plants (WWTPs) include thickening, stabilization and dewatering. Thickening and dewatering primarily reduce the volume of sludge, making it easier to handle and transport, while stabilization minimizes the potential for further biodegradation. Thickening removes free water and interstitial water trapped between solid sludge particles. After thickening, the dry matter content of the sludge reaches around 4–6%.

Following stabilization, the dewatering process removes capillary water, which adheres to the sludge particles due to adhesive forces. After dewatering, the dry matter content increases to around 20–30%. However, even after these basic treatment steps, the SS still contains a large amount of water—specifically intracellular water bound in the sludge cells—which cannot be removed by conventional treatment methods [2–5].

To remove intracellular water, thermal treatment is required. However, conventional gas-driven thermal drying systems consume large amounts of energy, which makes them economically unfavorable. As a result, SS solar drying has been developed over recent decades as an alternative. By utilizing solar energy for thermal treatment, operating costs are significantly reduced as most of the required energy is supplied from natural renewable sources. This makes solar drying an economically viable option for SS treatment.

Literature Review and State of the Art in the Field of Research

The first forms of SS solar drying emerged in the 19th century, a period when industrialization brought significant changes to lifestyles, infrastructure and waste management practices in European and North American cities. During this time, the first centralized sewage systems were developed, allowing for more efficient collection and discharge of wastewater. Early SS drying facilities looked like open drying beds where sludge was exposed to solar energy and natural ventilation, with the aim of reducing its volume and moisture content [6–8].

Despite growing awareness of the issue, SS treatment remained technologically and logistically challenging until the mid-20th century [9]. It was during this period that the first experimental studies of enclosed SS solar drying systems were conducted, using greenhouse-like structures that made the drying process independent of external environmental conditions. The so-called “greenhouse effect” allowed for a 35–45% reduction in the drying area required compared to conventional open-air option [10,11].

A major turning point in the development of SS solar drying technology occurred in the 1990s, when the first conventional SS solar drying facilities, similar to those used today, were constructed [12].

By the early 2000s, 48 conventional SS solar drying facilities had been built worldwide. Approximately two-thirds of these were constructed in Germany, Austria and Switzerland, with a smaller number in France, the USA, Italy and Australia. This marked the beginning of the first comprehensive research into SS solar drying technology from both technical and economic perspectives. Depending on input load, construction type, equipment configuration and other factors, the study made in 2003 determined an average investment cost of €30–60 per ton of evaporated water—significantly lower than the costs associated with conventional gas-powered thermal drying systems [13].

Shortly after the widespread construction of conventional solar SS drying facilities, the need emerged for a quantitative description of the drying process. Effective management of solar drying requires the formulation of expressions for evaporation rate as a function of environmental and control variables. Several studies from this period focused specifically on modeling heat and moisture transfer processes [14–16].

In addition to techno-economic analyses, the ecological aspect of SS solar drying, specifically the characteristics of sludge after drying, has received increasing attention [17–20]. One important study in this context was conducted by Bux et al. (2002), who analyzed the organic matter balance in SS during the drying process [21]. The results showed a 48% reduction in volatile organic matter following solar drying. This level of reduction classifies the dried SS as well-stabilized, meeting key requirements for reuse, including the standards set by the US EPA (United States Environmental Protection Agency). Similar findings have been reported in other studies as well [22–24].

Research conducted in Komotina, Greece, showed that solar drying led to a two-order-of-magnitude reduction in the concentration of coliform microorganisms [25].

Most studies concerning the hygienization of SS during the solar drying process have found that the quality of the dried SS does not meet the requirements for Class A classification under US EPA criteria. Concentrations of viruses and parasites decreased by 1 to 2 orders of magnitude during the process, reaching acceptable levels. Similar results were observed for *Salmonella* spp. and *Escherichia coli*. However, there was no significant reduction in the concentration of fecal coliforms [18,20,26].

Finally, Bennamoun [27] conducted research indicating that standalone solar drying of SS allows achieving SS quality at Class B level. To reach a higher quality level, i.e., Class A, it is recommended to combine the solar drying method with additional treatments, such as lime addition during the preceding sludge dewatering phase.

By 2010, approximately 200 solar SS drying facility had been built worldwide, with as many as 150 located in Europe. Numerous literature sources state that dried SS can be considered hygienized and energetically valuable material, with an energy potential comparable to lignite or brown coal (10–12 MJ/kg) [28,29].

The specific electricity consumption in SS solar drying is very low, amounting to only 20–40 kWh per ton of evaporated water [30]. In the case of forced ventilation, i.e., the use of fans for air exchange, energy consumption is approximately three times higher [31].

One notable example of best practice in the application of SS solar drying in the Mediterranean region was described by Oikonomidis and Marinos [32] who presented a one-year operational experience of a SS solar drying facility in the city of Paphos, Cyprus. Considering that Cyprus enjoys approximately 300 sunny days per year, the study confirmed that the Eastern Mediterranean offers exceptionally favorable climatic conditions for the application of solar drying as a method of thermal treatment of SS. A significant outcome of this project was the calculated annual evaporation rate, which amounted to 1.14 tons of water per square meter per year ($1.14 \text{ t H}_2\text{O}/\text{m}^2 \cdot \text{year}$). This value significantly exceeds all previously published data in the literature, which were mostly based on facilities located in Central European climatic conditions (e.g., Germany and Austria, regarded as pioneers in the development and application of this technology) [32].

By 2015, more than 300 SS solar drying facilities had been built across Europe, which stimulated intense research interest focused on optimizing the drying process. The research concentrated on various technological and operational aspects, including heat and moisture transfer dynamics as well as the management of system operating parameters. Yilmaz and Wzorek [33] analyzed the impact of sludge layer thickness on drying kinetics, as well as the frequency of daily sludge turning. The results showed that maintaining an optimal sludge layer thickness of about 15 cm combined with an adjusted turning frequency significantly improves drying efficiency.

Similar contributions were made by Krawczyk [34,35] and Song et al. [36]. Krawczyk developed a numerical model to simulate heat and moisture transfer during the solar drying process. This model enabled a better understanding of the internal process dynamics, particularly the effect of sludge turning.

A comprehensive study was conducted by Kurt et al. [37], analyzing the possibilities of thermal treatment of dewatered SS at 37 existing wastewater treatment plants (WWTPs) in Turkey. Out of a total of 191 WWTPs built in Turkey by that time, 37 were designed for some form of thermal treatment of SS. The analyzed WWTPs varied in technology and the range of dewatered SS quantities produced. A particularly interesting approach involved supplementing solar drying of SS in greenhouses with the integration of photovoltaic systems. It was assumed that at certain locations, average sludge dryness of 70% could be achieved using only solar drying in greenhouses, while reaching the target dryness of 90% required additional energy input from solar panels. For the economic calculations, unit values were taken from previous studies. The construction cost of SS solar drying facilities was estimated at $300 \text{ EUR}/\text{m}^2$, based on equipment manufacturer data from Huber and Wendewolf. The unit power of fans and electricity consumption data were taken from Seginer et al. (2007) [38].

In the context of experiences gained in Germany and Austria, where a significant number of SS solar drying facilities had been built by then, Dellbrugge et al. [39] conducted an analysis on the introduction of additional subsystems aimed at increasing the efficiency of solar drying. Specifically, for the first time, the possibilities of integrating underfloor heating and direct supply of warm air into drying halls were examined, thereby adding conductive and convective heat transfer modes to the predominantly solar (radiative) heat transfer [39].

Countries in North Africa and the Arabian Peninsula [40] also show great interest in applying solar drying of SS, primarily due to favorable climatic conditions. Belloulid et al. [41,42] warn of the growing challenge of SS disposal in Morocco. By that time, a total of 84 WWTPs had been built in the country, while an additional 108 were in the planning or construction phase. Despite significant infrastructural development in the wastewater treatment sector, a systematic solution for SS treatment and final disposal in these projects was completely lacking.

Systematic scientific research on solar drying of SS began in the early 21st century, with the first significant publications appearing in 2000. Between 2000 and 2024, the number of scientific papers on SS solar drying grew relatively slowly, based on a review of the Web of Science and Scopus databases, as shown in Figure 2. Specifically, the annual number of published papers increased from only five in 2005 to twenty in 2020 and then declined to thirteen in 2024. Also, most recent research has focused on understanding drying kinetics, that is, the parameters affecting the speed and efficiency of the process under various climatic conditions [24].

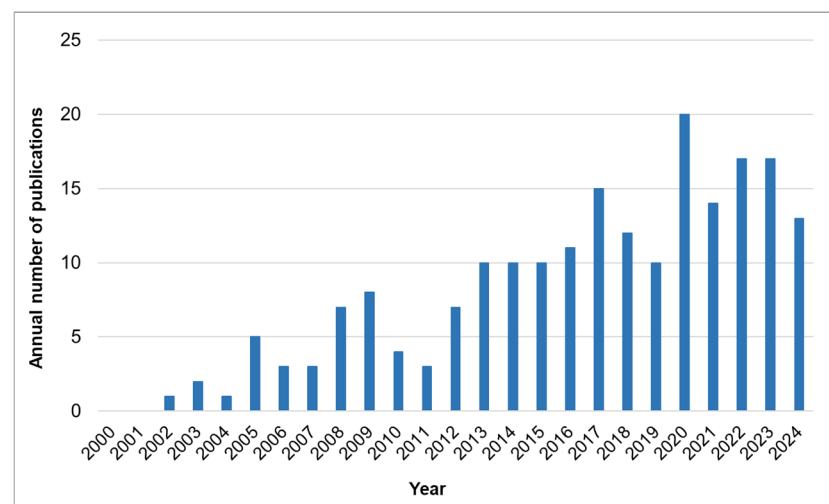


Figure 2. Number of publications in Web of Science and Scopus databases related to SS solar drying, 2020–2024.

In the past five years, according to published studies, solar drying of SS has been established as a widely accepted thermal treatment process. This is particularly relevant in the context of preparing SS for final disposal. For the further affirmation of SS solar drying as a standard technology for (thermal) treatment prior to its final disposal, additional research is necessary with the aim of improving the hygienic and health-related properties of the dried product. Improving SS quality directly impacts greater possibilities for its final disposal and/or reuse. In this regard, the topic of the presence and behavior of heavy metals in dried SS remains largely underexplored. Only a few studies have partially addressed the concentration of heavy metals in dried SS, although this parameter is one of the key criteria for achieving so-called Class A sludge according to US EPA standards [43,44].

Alongside hygiene-related issues, there is growing interest in approaching SS from the perspective of the circular economy. Although concrete research has yet to be conducted, the literature increasingly emphasizes the need to investigate the potential valorization of dried SS—both in terms of utilizing its energy value and in recovering nutrients, especially phosphorus, which is recognized as a natural resource undergoing gradual global depletion.

At the operational level, the broader application of solar drying of SS critically depends on optimizing the technology to reduce its dependence on climatic conditions [45]. In regions with favorable climates, especially during the summer months, high drying levels of SS (up to 90%) are easily achieved, which consequently enables significant reductions in pathogenic microorganisms, sometimes by 1 to 2 orders of magnitude. Conversely, in winter months, drying levels often drop to just 50 to 60%, substantially compromising process efficiency.

Precisely because of these seasonal limitations, in recent years, concepts of so-called hybrid SS solar drying systems have been developed. These systems combine solar radiation with additional forms of heat transfer, primarily convective methods (e.g., intro-

duction of warm air). Several recent studies have thoroughly analyzed such systems, highlighting their capability for continuous year-round operation with improved stability of drying results [46–49].

Based on the current research achievements and the authors' practical experience, it can be concluded that there is no clearly defined economic model for calculating the net present value (NPV) of all costs related to SS solar drying facility within a certain period. That includes all relevant parameters such as the location of the facility, local climatic conditions, the quantity and quality of SS to be dried, the desired dry matter content at the end of the process, etc. While a few previous studies have mentioned unit investment costs for such facilities, these are mostly based on relatively small samples of existing facilities in specific local areas. Even these few available studies provide mostly deterministic assessments, whereas approaches to adequately address uncertainty in key parameters, such as variability in local climatic conditions, fluctuations in SS composition and market-related factors (e.g., energy price), remain underdeveloped. Furthermore, the integration of policy and regulatory frameworks into economic and technical evaluations of SS solar drying facilities has been limited, even though these aspects critically influence investment decisions and long-term feasibility. The role of solar drying within circular economy principles, particularly in terms of resource recovery, valorization of dried SS and environmental benefits compared to alternative treatment methods, has been only partially explored. Addressing these gaps would provide a more holistic approach for assessing the sustainability and feasibility of SS solar drying technologies on a global scale, which would also help improve the accuracy of economic models. As for the economic aspect, on a global scale, there is a growing need to define an expert system that can calculate the NPV of a solar drying facility in a given region, based on the key influencing factors. Such an expert system could function as a straightforward, rapid, and effective decision-support tool for assessing the cost-effectiveness of solar drying of SS in comparison with alternative SS treatment methods. However, it should be emphasized that this study focuses exclusively on economic metrics (NPV), while environmental and social aspects such as greenhouse gas emissions, odor control, health risk reduction, or nutrient recovery are not considered. All these aspects should be addressed within a multi-criteria decision-making process aimed at selecting the optimal SS treatment and disposal solution for a given region. The expert system presented in this study is designed to support only the definition of the economic component.

2. Materials and Methods

2.1. Research Plan

Based on the previously reviewed available literature and past research conducted in the given field, conclusions have been drawn regarding the lack of studies and the potential benefits that could arise from them. By analyzing the current state of the field, the results of all case studies related to the economic validation of SS solar drying facilities were examined and their strengths and weaknesses were identified.

In Section 2.2, the methodology for dimensioning and designing the SS solar drying facility is described. This includes the process of calculating solar drying facility parameters, defining its dimensions, required equipment specifications and other relevant parameters. This calculation will serve as a foundation for later estimation of the investment as well as operation and management costs of the facility.

The main part of this research is the development of an expert support system for assessing the cost-effectiveness of building SS solar drying facility based on calculation of its NPV within a certain period. The system is created within the widely accepted and user-friendly interface of Microsoft (MS) Excel. One of the fundamental assumptions of

this expert system is to allow users to easily and quickly estimate the total or unit costs of construction, operation and maintenance of a SS solar drying facility (for various facility sizes, sludge volumes and characteristics and other specific values of different relevant parameters), without the need for prior plant dimensioning or the subsequent preparation of an approximate cost estimate.

For the purposes of this work, a database was developed that includes a large number of hypothetical examples with varying values of key influencing factors and boundary conditions. All relevant factors that are considered important for the cost analysis of construction, operation and maintenance of SS solar drying facilities, including further treatment and/or disposal of SS were varied. The preparation of the database was part of the analytical component of the research, with the author's own professional expertise also applied. For each case included in the database, a prior dimensioning of the SS solar drying facility was carried out, along with corresponding approximate cost estimates. That includes construction, operation and maintenance costs, as well as actual costs for further SS treatment and/or disposal.

The database was created for the territory of the Republic of Croatia. Given the specific characteristics of continental and coastal Croatia, the database includes a sufficient number of hypothetical examples representative of both regions. This is particularly relevant to differences in solar radiation rate, which is one of the key factors in the facility dimensioning process. It is important to emphasize that all characteristic geographic areas of Croatia are covered—continental, Mediterranean and mountainous zones. In this way, the available database will be applicable to a broader regional area, not only encompassing the whole of Croatia but also extending to a much wider region.

The database is designed in such a way that, with certain modifications (e.g., changes in unit prices of individual items or climate conditions defined by evaporation rates), it can also be successfully applied outside the borders of Croatia, provided that, for a given real-life case, the values of key characteristics fall within the limits covered by the database. Accordingly, the same methodology can be extended to other regions, provided that certain input parameters (such as unit costs and evaporation rates) are redefined, after which the neural network (NN) should be retrained and tested. The work related to the preparation of this database has been continuously carried out by the authors over the period 2020–2024. For the purpose of populating the database, a large number of hypothetical cases were defined, while some cases correspond to actual projects from practice, based on the authors' previous experience in the design, construction, operation and maintenance of several SS solar drying facilities. The definition of hypothetical examples was deemed essential by the authors for the development of a high-quality comprehensive database. It should be emphasized that each of the defined hypothetical settlements corresponds to the real conditions and describes actual scenarios. The described database is an integral part of the expert system being developed.

The database will be integrated into an NN. Since the objective of this work is to develop an expert system within a unified user interface, the NN must be compatible with the MS Excel interface. In this context, the software package NeuralTools (Version 8.0) developed and distributed by Lumivero (Denver, CO, USA), was selected. This software package is designed as an add-in module for MS Excel.

After preparing the complete database, the training process of the NN will be conducted. Based on the learned patterns (rules), NNs are capable of extrapolating estimated output values for a new set of input data. These relationships remain hidden within the structure of the NN itself, which is why it is often referred to as a "black box" model. However, in addition to generating output results, the NN also provides insight into the relative influence of each input variable on the final outcome [50].

Once the training is completed, the NN will undergo testing using 20% of the samples (scenarios/cases) from the input database. The testing phase will evaluate how accurately the NN predicts output values. This process will help determine whether the trained network can be reliably used for estimating new scenarios with unknown values of the dependent variable.

In the final phase, the trained and tested NN will be used to estimate outputs for a larger number of hypothetical cases to verify the correctness of its operation.

The output generated by the expert system refer to the cost assessment of constructing, operating and maintaining a specific SS solar drying facility, including the subsequent treatment or disposal of the dried SS. In addition, the expert system will provide cost estimates for the disposal of dewatered (but not dried) SS as an alternative solution, either through transport to a regional center where further treatment (without imposing constraints on the deployment of any technology) and/or final disposal (by landfilling or reuse) is foreseen, or by transfer to another legal entity authorized for further treatment and/or final disposal. This approach enables a direct economic comparison between SS solar drying facilities and the alternative options of transporting dewatered SS to a regional center or handing over of sludge to another entity for subsequent treatment and disposal, thereby supporting more informed decision-making regarding the cost-effectiveness of constructing SS solar drying facilities. Thus, the expert system integrates diverse treatment and disposal solutions into a single unit cost, which can be adjusted to reflect real market conditions and realistic treatment and disposal practices. However, any modification of these values requires retraining and retesting of the NNs.

2.2. Fundamentals of Dimensioning a SS Solar Drying Facility

The SS solar drying facility consists of a prepared surface onto which dewatered sludge is spread. This surface is most commonly constructed as a traditional reinforced concrete slab, although alternatives such as asphalt or micro-reinforced concrete bases also exist. Regardless of the selected drying technology, the surface must be flat with a tolerance of approximately 1 cm/m to ensure proper operation of the sludge turning device and overall process efficiency. If the base is built as a reinforced or micro-reinforced concrete slab, it is essential to ensure the concrete meets the required class and exposure categories regarding corrosion and potential chemical impacts from the SS.

Reinforced concrete side walls are constructed on the concrete base, designed to the appropriate concrete class and exposure category. The height of the side walls depends on the selected technology, but a typical height is 80–100 cm from the finished ground level. A steel structure is then mounted onto the side walls. The dimensions and thicknesses of the steel profiles, as well as the spacing of the truss frames, are determined through structural calculations. As these are lightweight structures, the dominant loads are snow and wind (in addition to the self-weight of the structure). The total height from the ground slab to the ridge is approximately 6.0 m, with a roof inclination of 25%.

Depending on the chosen roofing material (Table 1), an aluminum or steel substructure is installed on the main steel frame. Transparent walls and roofing, made from materials with a high solar transmission factor, are mounted on the structure to enable maximum solar radiation transmission. Currently, the market typically offers roofing materials that fall into two basic categories:

- Polymer-based materials (e.g., PE foil, ETFE foil, polycarbonate sheet);
- Glass cover structures (ESG).

Table 1. Main characteristics of roofing material.

Property	Characteristics of Roofing Material			
	PE Foil	ETFE Foil	Polycarbonate	ESG
Material	Polyethylene	Ethylene-tetrafluoroethylene	Polycarbonate sheets	Safety glass
Thickness	100–200 μm	150–200 μm	6–10 mm	6 mm
UV warranty	5–10 years	15–20 years	10 years	>20 years
Tear strength	20–25 N/mm ²	>40 N/mm ²	2400 N/mm ²	/
Transparent	85–90%	90–95%	85–90%	90–95%

The walls and roof form an enclosed chamber—a greenhouse, on the floor of which SS is spread in a layer approximately 20–30 cm thick. The drying process is based on the absorption of solar radiation by the sludge, which causes an increase in temperature inside the greenhouse. The drying rate of the sludge depends on the vapor pressure difference between the heated sludge and the air in the greenhouse. Since the partial pressure of water vapor in the air directly depends on absolute humidity, the best drying results are achieved under conditions of heated sludge and dry air in the drying hall.

In terms of efficient water removal from sludge, there are two key challenges to address: the attractive forces between water molecules within the sludge and existing humidity within the drying halls.

The attractive forces between water molecules hold the moisture within the sludge and hinder its efficient removal. To break these bonds, thermal energy must be supplied. By continuously turning the sludge in such a way that the moist layer is always exposed on the surface and using solar energy that acts on this surface layer, efficient water removal is enabled through evaporation into the drying hall's interior space. As the water evaporates, the concentration of water vapor in the air increases. Depending on the temperature, air can hold a certain amount of water vapor without condensation occurring. To prevent this and thereby improve the efficiency of the SS solar drying process, continuous air exchange must be ensured within the facility.

Air exchange in solar drying halls can be either natural or forced ventilation. In the case of natural ventilation, moist air is evacuated by opening a movable part of the roof that runs the entire length of the hall. The roof is closed during rainfall. Fresh air typically enters through lateral (side) openings. In the case of forced ventilation, the entire structure is completely enclosed, with louvered inlets for fresh air and fans for extracting moist air mounted on the front and rear facades of the drying halls. The advantage of this method is the ability to monitor drying process efficiency, as the exact air exchange rates in the halls can be calculated. However, the drawback is a 3- to 4-times higher electricity consumption compared to natural air exchange.

During the drying process, moisture stratification can occur within the sludge layer. A potential issue arises if a layer of humid air forms on the sludge surface, which hinders efficient evaporation. To address this, vertical axial fans are used to recirculate air within the drying halls and prevent vertical stratification. The number of fans is determined through a technological calculation, and they are evenly distributed across the entire length and width of the drying hall [51].

Figure 3 shows a schematic view of the air exchange system (depicting forced air exchange) and the air recirculation system in SS solar drying halls.

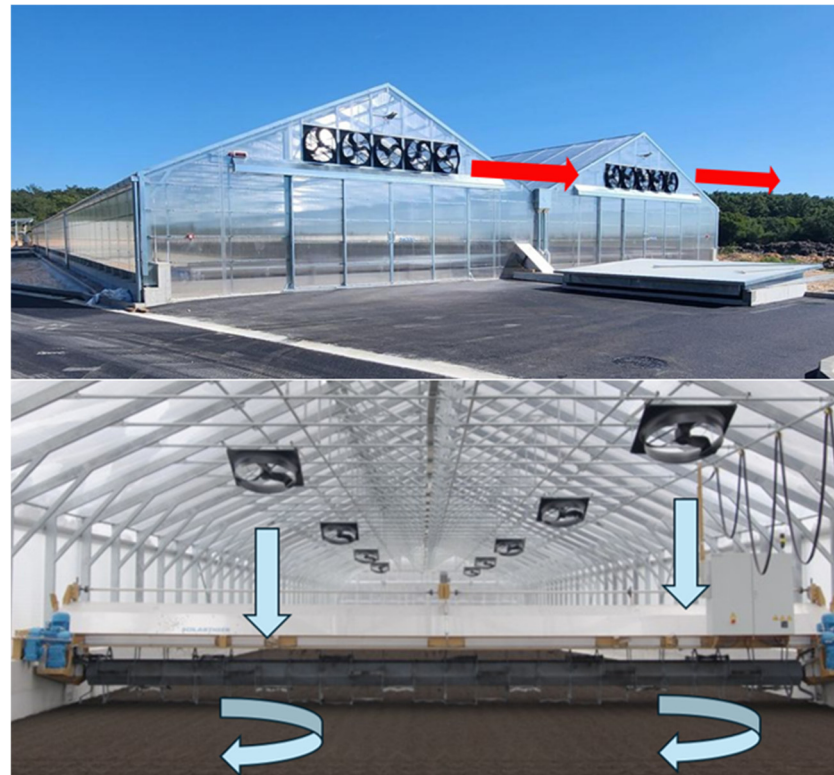


Figure 3. Schematic view of the air exchange system and air recirculation system in SS solar drying facility.

One of the most important elements in the entire drying process is the sludge turning device. Today, several different types of sludge turning devices are available on the market, each with its own sub-variants, which can generally be categorized into three basic types: Ratus, Thermo-System and IST [13]. Currently, the most widely used is the “IST” type, applied by the majority of global companies involved in the design and construction of SS solar drying facilities.

The continuous drying method implies the constant production of dried sludge, which, before being transported to its further treatment or its final disposal site, needs to be temporarily stored. The handling of sludge including delivery of dewatered sludge, removal and storage of dried sludge can be done in a fully automated manner using appropriate conveyors or manually using sludge loaders. The automated approach is certainly cleaner but requires significantly higher investment and operating costs and is generally subject to inspection for explosive atmospheres (requiring “ex” rated equipment).

All equipment in the facility is operated from a central control panel that manages the sludge turning devices, fans, lighting, conveyors, etc. The central control system and control panel are usually installed in a separate container unit outside the drying halls, but in their immediate vicinity to allow access to the entire facility. Due to safety regulations and personnel protection, remote operation of the process is not recommended.

When it comes to the calculation and dimensioning of a SS solar drying facility, the first step is to define the input load in terms of the quantity and quality of SS delivered for drying. Typically, the SS is dewatered with a dry matter content of 20–30%, though it is also possible to receive sludge with a lower dry matter content or even thickened (non-dewatered) sludge. In such cases, drainage channels for capillary and partially trapped water are constructed within the floor structure.

For calculation purposes, it is important to distribute the input loads on a monthly basis to more easily define a SS drying facility in the following steps. To determine the

exact required surface area of the solar drying facility, in addition to the total quantity of dewatered sludge, the actual dry matter content at the inlet and the desired dry matter content at the outlet, it is necessary to collect data on the climatic conditions at the specific location. Several important factors affect drying efficiency, with solar radiation and air temperature being the most significant. When discussing climate data for a particular area, the relevant information is usually obtained from the national hydrometeorological institute.

All literature sources identify solar radiation, air temperature and ventilation rate as the three most influential variables in the evaporation calculation. In addition to these, current sludge moisture content and air recirculation rate have also proven to be important. When these five main influencing variables are selected (solar radiation, temperature, air exchange, current sludge moisture and air recirculation), the evaporation rate is defined according to a multiplicative model [52]:

$$E = \rho \times Q_V \times 1.962 \times 10^{-11} \times (R_0 + 1100)^{2.322} \times (T_0 + 13.0)^{1.292} \times (Q_V)^{-0.577} \times (Q_m + 0.0001)^{0.013} \times (\sigma + 0.26)^{-0.353} \quad (1)$$

where

E —evaporation (mm/h);

ρ —air density (kg/m³);

Q_V —air exchange rate (m³/m²·h);

R_0 —solar radiation (W/m²);

T_0 —air temperature (°C);

Q_m —air recirculation rate (m³/m²·h);

σ —dimensionless coefficient of current sludge moisture.

Experience in the design and sizing of SS solar drying facilities indicates the need for correction of the above equation. Specifically, this is a regression equation derived from the analysis of a specific facility, whose results and the influence of individual variables may not be applicable in other cases. This is especially true for the air exchange variable, whose impact has a nonlinear character. In practice, air exchange rate is linked to the absolute humidity of the air inside the drying halls. Operationally, ventilation systems are activated when internal absolute humidity exceeds a predefined threshold and are deactivated when the value falls below minimum threshold. This mode of operation clearly shows that air exchange is not a stationary variable but rather fluctuates across different months and climatic conditions. For this reason, in the process of dimensioning and calculating process kinetics, it is necessary to introduce correction factors for the air exchange variable on a monthly basis, in order to adapt the equation to the actual climatic conditions of a given location.

Based on all input parameters and the correction of the above evaporation equation, the unit annual amount of water evaporated from the sludge is calculated and distributed by month. Figure 4 shows an example of a diagram of monthly evaporation rate values on specific SS solar drying facility.

Based on the resulting evaporation diagram and the quantity and quality of the (incoming) dewatered sludge, the total amount of water that needs to be removed from the sludge can be determined. From this, the required surface area of the solar drying facility is calculated using the ratio of the annual amount of water to be removed from the sludge ($m(\Delta H_2O)$) and the unit annual evaporation rate (E'_{ann}):

$$A = \frac{m(\Delta H_2O)}{E'_{ann}} \quad (2)$$

Based on the defined surface area, the number and dimensions of the drying halls are determined.

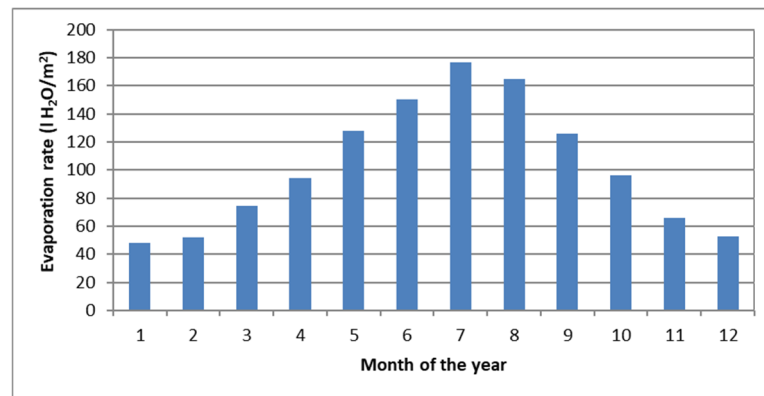


Figure 4. Monthly evaporation rate values—example (l H₂O/m²).

2.3. Creating the Database

The database created in this study refers to the development of a large number of cases (scenarios) of SS solar drying facilities with the goal of calculating the economic aspects of construction and operation for each case over a defined period and comparing the results with the costs of transporting/disposal of undried (dewatered) SS.

For each scenario, a calculation of investment as well as operation and maintenance costs was conducted, covering all elements of the solar drying facility. These were grouped into logical units with associated unit prices for construction, operation and maintenance. The scenarios differ in terms of input loads, SS quality, methods and types of solar drying, structural types and its characteristics, ventilation methods, etc. In fact, a very large number of variant solutions were developed based on the adopted design guidelines for such facilities, as described in the previous chapter.

In defining each scenario, a pre-prepared database of unit costs for construction, operation and maintenance of all characteristic items was used. A major advantage of the created database lies in its automated structure, which allows end-users to easily adjust it to real market conditions. This means that users can simply modify unit costs of construction, operation and maintenance according to new market conditions, with automatic correction of the Net Present Value (NPV) in all generated scenarios. This increases the value of the database, as it can be adapted to various and time-varying circumstances (e.g., change in currency, unit prices of specific items, inflation, etc.). Any change in an input parameter within the prepared database requires retraining and testing of the NN to ensure it continues to provide accurate predictions under the new conditions.

The final outcome is the calculation of the net present value (NPV) for each defined scenario, which will subsequently serve as the output (result) variable in the NN training process.

The first step in creating the database was to define the range of SS input loads as the fundamental input data for dimensioning the solar drying facility. These input loads are expressed as the total annual amount of dewatered SS to be dried (t/year). The range of loads was defined from 75 t/year of dewatered SS as the minimum input value (equivalent to about 1000 persons equivalent (PE)) to a maximum of 20,000 t/year (equivalent to about 270,000 PE).

To ensure the NN “learns” these specific characteristics, a dense distribution of input loads was defined. In order to avoid overloading the NN with an excessive number of scenarios, the input loads were divided into two groups: 75–10,000 t/year and 10,000–20,000 t/year. Separate training and testing of the NN is planned for each group.

In addition to the amount of SS entering the drying process, another important input parameter is the dry solids content of the dewatered sludge delivered to the solar drying

facility. It is important to emphasize that the database includes only dewatered SS. Raw SS (from primary and/or secondary clarifiers) or merely thickened SS is not analyzed, since such solutions are considered inefficient at the global level.

In this context, the scenarios included a range of dry solids content from 20% to 30%, which is considered a realistic range achievable through conventional SS dewatering processes.

Similarly, for dried SS, a target range of final dry solids content was also defined. According to global practice, the minimum dry solids content typically achieved through solar drying and used in facility design is 75%. The maximum value varies depending on several influencing factors, but is usually assumed to be 90%.

Based on these three input variables, the next step in creating the database was to calculate the amount of water that must be removed from the SS for each defined combination: SS quantity $\rightarrow$ dry solids content of the dewatered SS $\rightarrow$ target dry solids content of the dried SS.

After defining the required input load, the next step is to determine the unit evaporation rate, which is then used to calculate the required working surface area (the area onto which the sludge is spread) for SS solar drying. The evaporation rate is calculated using the multiplicative model described in the previous chapter, which considers five key influencing variables.

Since the database aims to cover the entire territory of the Republic of Croatia, the climate parameters first had to be standardized by defining climate regions based on the predominant climate types in each area.

One of the most commonly used global climate classification systems is the Köppen climate classification (also known as the Köppen–Geiger classification). Developed in the late 19th and early 20th centuries, the system classifies most of Croatia as having a temperate (C-type) climate, either moderately humid temperate or Mediterranean, while a small portion of the country above 1200 m elevation falls under D-type (snow forest or boreal) climate [53,54].

Ultimately, the following climate types are defined for Croatia:

Csa—Mediterranean climate with hot summer;

Csb—Mediterranean climate with warm summer;

Cfa—moderately warm humid climate with hot summer;

Cfb—moderately warm humid climate with warm summer;

Df—humid boreal climate.

For this database, the climate types used were Csa, Cfa, and Cfb, as they cover the vast majority of the territory of the Republic of Croatia. Figure 5 shows a distribution of climate types in Croatia (according to Köppen).

To categorize the evaporation values according to the described climate types, a comprehensive calculation of evaporation rate was carried out within the development of the database in this study, covering 35 different locations across the Republic of Croatia (Figure 6). After manually calculating the evaporation value for each individual location, each climate type was assigned its corresponding average value.

The selected average values of evaporation rate by climate type are given below:

Csa—Mediterranean climate with hot summer $\rightarrow E' = 1.32 \text{ t H}_2\text{O/m}^2 \cdot \text{year}$;

Cfa—moderately warm humid climate with hot summer $\rightarrow E' = 1.20 \text{ t H}_2\text{O/m}^2 \cdot \text{year}$;

Cfb—moderately warm humid climate with warm summer $\rightarrow E' = 1.00 \text{ t H}_2\text{O/m}^2 \cdot \text{year}$.

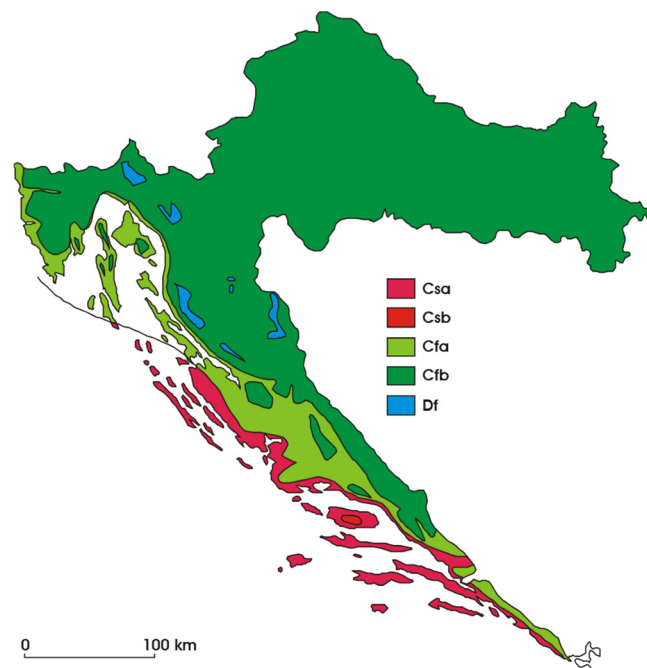


Figure 5. Geographical distribution of climate types according to Köppen in Croatia (adapted with permission from Ref. [55]).



Figure 6. Display of locations that were used for the calculation of evaporation rate.

For the previously defined amount of water to be removed from the sludge and the selected unit evaporation rate according to the climate type, the total required net (working) surface area for SS drying is calculated using the Formula (2).

Once the required net drying area has been calculated, the dimensions of the drying halls are determined by setting the width of a single hall to the maximum width of a conventional sludge turning device (“IST” process), which is 12 m. Based on the calculated area and defined width, the total length of the working surface for SS drying is determined.

The number of required drying halls (lines) is determined based on the total calculated length. For practical reasons, the maximum length of a single drying hall is limited to 115–120 m.

To ensure calculation accuracy, an approximate cost estimate of facility construction is broken down into characteristic groups depending on the type of construction work. These groups refer to: ground works, concrete works, steel construction, cover structure works, installation of electrical and mechanical equipment, defining the sludge manipulation method, cost of project documentation, etc. For each group, possible variants were defined, based on which unit construction costs were established and later used as variable inputs in the database.

After defining the unit construction cost values, the total unit construction cost of a SS solar drying facility was calculated and expressed in EUR/m². This value is then divided into two components: the unit cost of the construction part and the unit cost of the mechanical and electrical equipment installation. This division is necessary for the later calculation of operation and maintenance costs, as well as depreciation, which are calculated as a percentage of the investment cost (with different percentages applied to the construction part and equipment).

The unit costs (expressed in EUR/m²) are multiplied by the previously calculated drying area and number of drying halls, resulting in the total initial investment cost (construction cost) of the SS solar drying facility.

It is important to note that in this work, land acquisition costs for building the SS solar drying facility are not included in the investment costs. According to global practice, most solar SS drying facilities are constructed within the premises of the wastewater treatment plant, which is usually owned by public water service providers. This approach allows SS treatment and drying to be conducted at the same location, simplifying the handling of dewatered SS to the drying facility.

The unit operation and maintenance costs, including depreciation, include the following:

1. Electricity consumption for the basic operation of the SS solar drying facility (kWh/t of sludge);
2. Electricity consumption for air treatment (kWh/1000 m³ of air);
3. Unit labor cost (EUR/day);
4. Unit cost of construction maintenance;
5. Unit cost of mechanical and electrical equipment maintenance;
6. Unit depreciation cost of the construction part;
7. Unit depreciation cost of mechanical and electrical equipment;
8. Unit cost of transport of dried SS;
9. Unit cost of further treatment of dried SS at a regional center (without imposing constraints on the deployment of any technology) including its final disposal (without imposing constraints on the deployment of any disposal route).

In this study, two scenarios for dried SS disposal were considered:

1. Treatment of dried SS at a regional center including its final disposal;
2. Handing over of dried SS to another legal entity for further treatment and final disposal.

In the scenario involving treatment at a regional center, the database was prepared by considering different options of transporting the dried SS to the center for further processing/disposal. Two options were analyzed for transporting the SS:

1. Using the public service provider's own trucks;
2. Outsourcing transport to an external company.

Four distance categories were defined for transport to the regional center, each with an assigned unit transport cost:

1. <30 km
2. 30–60 km
3. 60–100 km
4. >100 km

The final step is calculating the NPV of the total investment, operation, maintenance, depreciation and final SS disposal costs, within the 30-year period of time. NPV is a discounting method used to assess the value of cash flows associated with a particular project, considering the time value of money. The time value of money assumes that money available today is worth more than the same amount in the future because of its earning potential through investment.

The database was created manually in MS Excel, based on a large number of real and hypothetical scenarios with different input loads, sludge quality (in terms of dry matter content), etc. The resulting database was prepared for training and testing an NN and includes 12 dependent variables and one independent (output) variable in the form of NPV.

A complete overview of the variables used in the NN model is presented in Table 2.

Table 2. Variant parameters in the process of creating an NN model.

Parameter	Variable type	Variants
Sludge input load	Independent numeric variable	Load range from 75 to 20,000 t/y
Dry matter content in dewatered sludge	Independent numeric variable	20–30%
Dry matter content in dried sludge	Independent numeric variable	75–90%
Climatic region according to the Köppen classification	Independent category variable	A. Climate type Cfb B. Climate type Cfa C. Climate type Csa
Soil category	Independent category variable	A. Type A B. Type B C. Type C
Unit load (dead load + wind + snow)	Independent category variable	A. 0.5–1.5 kN/m ² B. 1.5–2.5 kN/m ²
Type of roof structure	Independent category variable	A. PE foil B. ETFE foil C. Polycarbonate sheets D. ESG
Sludge manipulation	Independent category variable	A. Automated input B. Loader
Air treatment	Independent category variable	A. YES B. NO
Air exchange	Independent category variable	A. Natural air exchange B. Forced air exchange
Distance of the SS solar drying facility from the regional center	Independent category variable	A. <30 km B. 30 to 60 km C. 60 to 100 km D. >100 km
Method of transporting sludge by truck	Independent category variable	A. Own vehicles B. External company
Net Present Value	Dependent variable	

Given the large number of defined input loads as well as the possible options for all mentioned variables, the database in the case of transport and disposal of SS at a regional center ultimately resulted in a total of 599,040 generated scenarios, representing all possible combinations of the previously listed variables. For easier data management, the database was divided into four smaller datasets by splitting the input load range of 75 to 20,000 tons per year into two groups: 75 to 10,000 t/year and 10,000 to 20,000 t/year. In addition, the database was further divided according to the mode of SS transport to the regional center (own transport or outsourced to an external company). In this way, four databases were created, each containing 149,760 scenarios.

If the option of delivering dried SS to another legal entity for disposal is selected, this constitutes a fifth database, which is slightly smaller than the previous ones and contains a total of 74,881 scenarios.

2.4. NN Training and Testing

In NeuralTools, the user is offered the ability to configure various aspects of the training process. Among the key settings is the option to simultaneously conduct training and testing, where a portion of the data is randomly selected for independent model evaluation. According to recommendations for the use of NNs, the defined data split between training and testing is 80% to 20%. This means that 20% of the initially defined database is used for testing and is excluded from the training process. This ensures the evaluation of the network's ability to generalize knowledge to examples that were not used during training. During training, the program continuously monitors the validation error. If the validation error begins to increase while the training error continues to decrease, this indicates overfitting, and the training stops (early stopping).

During the training phase, it is also possible to analyze the sensitivity of the model to individual input variables using the "Calculate Variable Impacts" command. This analysis quantifies the contribution of each variable in the decision-making process, expressed as a relative percentage. The results provide insight into the importance of specific features, which helps identify less relevant variables that may be excluded from further iterations of the model. This approach not only simplifies the model structure but can also improve its accuracy and stability. However, interpreting the sensitivity analysis results requires caution. A high relative difference in the impact of two variables does not necessarily mean that the lesser variable is completely irrelevant. In some cases, variables with small but specific influence can be crucial for improving model precision, especially in borderline situations.

NeuralTools supports multiple NN architectures adapted to different types of predictive tasks. For classification problems and category prediction, two types of networks are available: Probabilistic Neural Network (PNN) and Multilayer Feedforward Network (MLF). For numerical (continuous) prediction, it is possible to use either the MLF network or the General Regression Neural Network (GRNN), which is functionally related to the PNN.

In this study, the GRNN type was chosen, as it has proven to be the most suitable option in scientific research involving NNs, particularly when the goal is to build a model that is efficient, stable, and sufficiently flexible for various types of data. Figure 7 shows an NN training flow.

After the network training process is completed, it is possible to analyze the results using statistical indicators that show how successfully the network was trained. One of the key indicators is the percentage of bad predictions (% Bad Predictions), which represents the proportion of cases in the training set where the NN's estimates deviate from the actual values. In addition, it is also possible to analyze the mean absolute error, standard deviation of errors, and other statistical parameters.

The testing process of an NN aims to quantify the level of error the trained network produces when determining the value of the output variable. Testing verifies how effective the network is at generalizing the learned patterns and to what extent it can reliably predict output values based on new, unseen data.

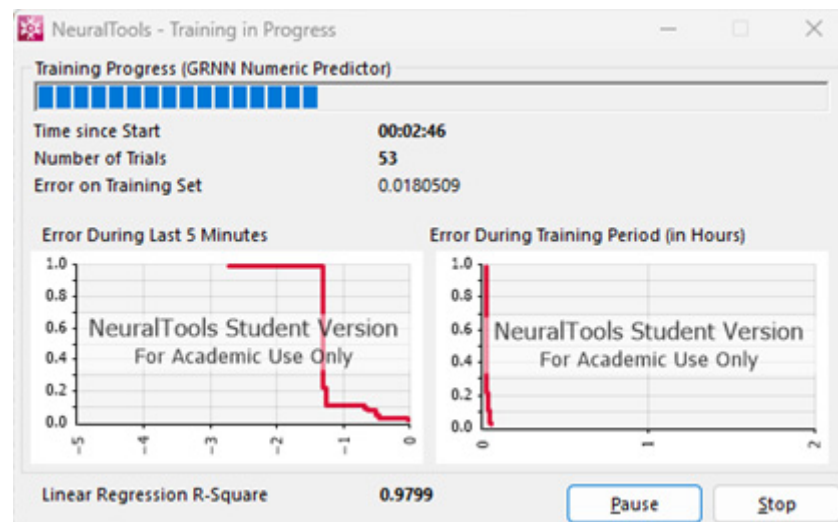


Figure 7. View of the NN training flow.

The test data is selected from the original dataset, and it is crucial that this sample is separated before the training process begins. This ensures that the network does not use information it has already “learned” during testing, which would compromise the objectivity of the evaluation. According to the automation built into the NeuralTools software, 20% of the total predefined dataset (the developed database) is used for testing, while the remaining portion is allocated for training the NN.

The value of the testing process lies in its ability to assess the network's performance on new, unknown scenarios based on known input-output relationships within the test set. The results of the testing are presented in the form of statistical indicators similar to those used during the training phase.

3. Results

After the network training process is completed, NeuralTools provides an overview of a series of statistical and graphical indicators that allow for an evaluation of the quality of the trained (learned) model. These results include the following:

1. Error Tolerance Definition

NeuralTools provides standard guidelines for assessing result validity as follows:

- Accuracy above 70% (up to 30% deviation): This value is automatically defined in NeuralTools as the threshold between good and poor results. It is considered the minimum acceptable for many classification tasks. In complex or nonlinear models, lower accuracy may be tolerated if no better model is available.
- Accuracy between 80 and 90%: Good accuracy, results are generally reliable and useful for decision-making. If the data is balanced and there is no significant overfitting (large discrepancies between training and testing results), such models are often very dependable.
- Accuracy above 90%: Excellent accuracy, but caution is required due to the possibility of overfitting, especially if there is a significant gap between training and testing performance.

2. Statistical Accuracy Analysis of the Model

Key statistical indicators include:

- Root Mean Squared Error (RMSE)—a value that measures the model's average error. Lower RMSE indicates higher model accuracy.
- Mean Absolute Error (MAE)—the average absolute difference between actual and predicted values, regardless of the direction of the deviation.
- Standard Deviation of Absolute Error—measures the variability of model errors. A higher value indicates less consistent predictions.
- R^2 (Coefficient of Determination)—shows how well the model explains the variance in the output variable. Values closer to 1 indicate high model accuracy.

3. Graphical Representation of Results

NeuralTools also offers several useful graphs for visual model evaluation:

- Histogram of residuals—shows the distribution of prediction errors. A narrow and centered distribution around zero suggests high model accuracy.
- Scatter plot—shows the relationship between actual and predicted values. Ideally, all data points should lie on the diagonal line $y = x$, indicating high prediction accuracy.
- Error vs. Actual or Predicted Values Plot—used to compare a range of values in order to detect patterns or systematic deviations.

Below are the results for a total of five NN models. Four models relate to the training of a database involving the option of transporting and disposing of SS at a regional center. The fifth model represents the option of handing over the SS to another legal entity for disposal.

3.1. Trained Input Load Base from 75 to 10,000 Tons/Year, with the Option for Own Transport to the Regional Center (NN Model No. 1.1)

The prepared database contains a total of 149,760 scenarios, of which 119,808 (80%) were used for training (learning) the NN. The remaining 29,952 (20%) scenarios were used to test the NN. Of the total number of tested cases (29,952), 29,853 or 99.7% have an accuracy of more than 95% (Table 3, Figure 8). The analysis results of the database thus indicate a very high accuracy and reliability of the NN model.

Table 3. Statistical accuracy analysis for trained and tested network (NN model 1.1).

Linear Predictor vs. Neural Net		
Parameter	Linear Predictor	Neural Net
R-Square (Training)	0.9729	-
Root Mean Sq. Error (Training)	859,743.18	24,794.94
Root Mean Sq. Error (Testing)	863,757.06	68,389.89

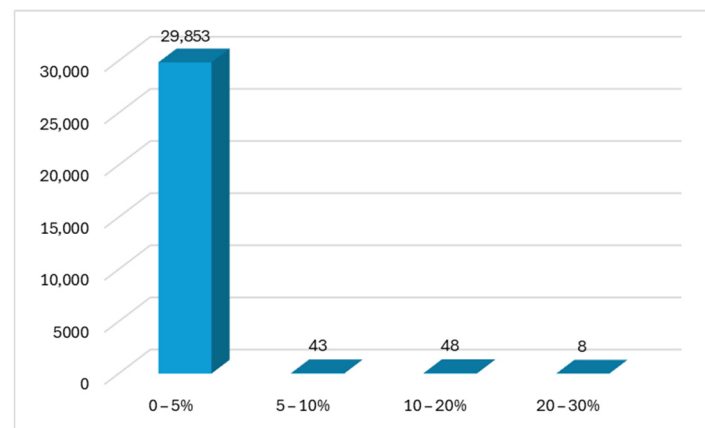


Figure 8. The number of tested cases in relation to the error tolerance of the trained and actual values (NN model 1.1).

Figures 9 and 10 show the error histograms for the trained and tested parts of the NN. Looking at the absolute error values, a rather narrow and centered distribution around zero can be observed, which according to this indicator, suggests a high accuracy of the model.

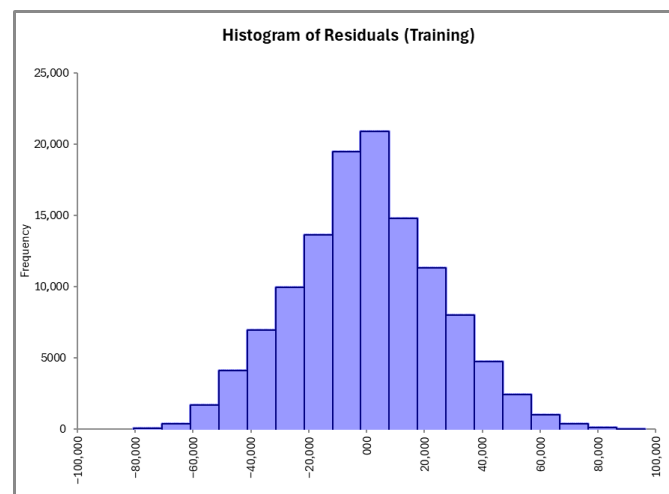


Figure 9. Histogram of residuals (Training) (NN model 1.1).

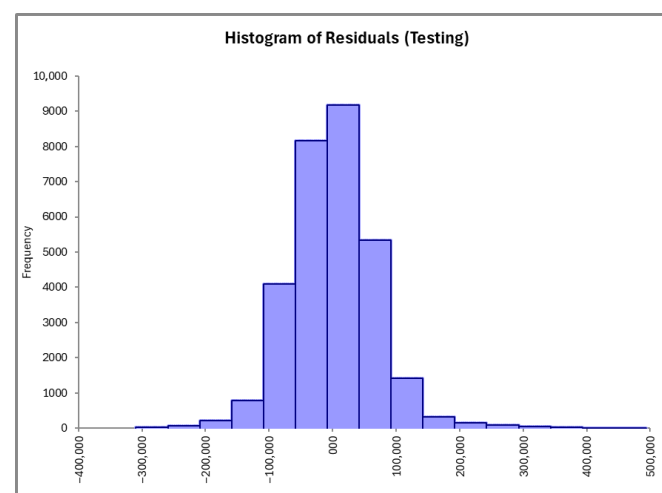


Figure 10. Histogram of residuals (Testing) (NN model 1.1).

The scatter plot between the actual and tested values is shown in Figure 11. The results indicate a very high accuracy of the model, as all values lie in the narrow range along the $y = x$ diagonal.

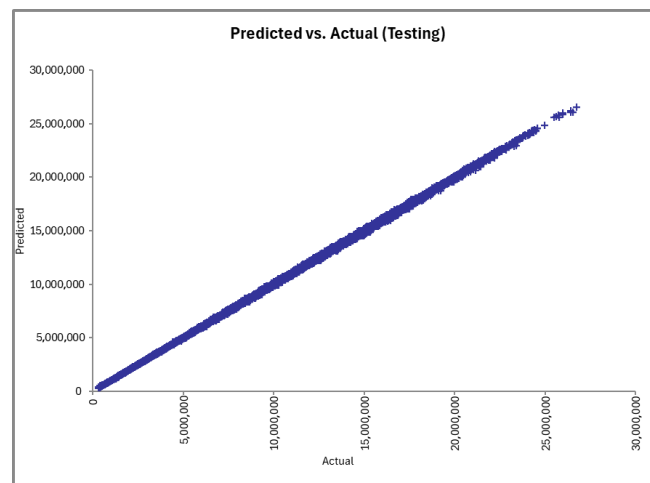


Figure 11. Predicted vs. actual values (Testing) (NN model 1.1).

3.2. Trained Input Load Base from 10,000 to 20,000 Tons/Year, with the Option for Own Transport to the Regional Center (NN Model No. 1.2)

Like the previous database, this one also contains 149,760 scenarios, of which 119,808 (80%) were used for training (learning) the NN. The remaining 29,952 (20%) scenarios were used to test the NN. Of the total number of cases tested, all 29,952 (100%) have an accuracy of more than 95% (Table 4, Figure 12). Compared to the previous model, this model has significantly higher values for the output variable (NPV), as it uses a load range of 10,000 to 20,000 tons/year of SS. As the actual value increases, the error percentage of the trained NN model decreases.

Table 4. Statistical accuracy analysis for trained and tested network (NN model 1.2).

Linear Predictor vs. Neural Net		
Parameter	Linear Predictor	Neural Net
R-Square (Training)	0.9604	-
Root Mean Sq. Error (Training)	1,264,380.44	67,594.42
Root Mean Sq. Error (Testing)	1,268,562.15	141,049.03

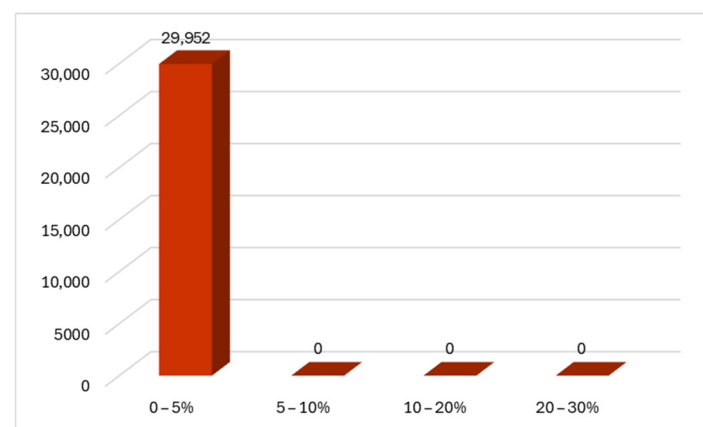


Figure 12. The number of tested cases in relation to the error tolerance of the trained and actual values (NN model 1.2).

Figure 13 shows the scatter plot between the actual and tested values. The results indicate a very high accuracy of the model, as all values lie in the narrow range along the $y = x$ diagonal.

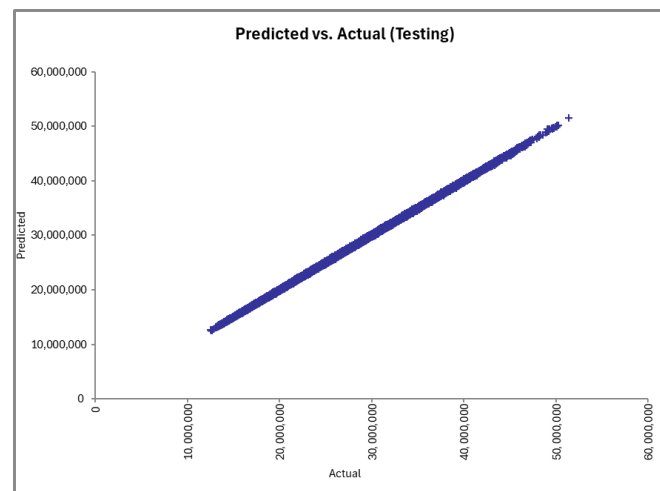


Figure 13. Predicted vs. actual values (Testing) (NN model 1.2).

3.3. Trained Input Load Base from 75 to 10,000 Tons/Year, with the Involvement of an External Company for the Transport of SS to the Regional Center (NN Model No. 1.3)

The model of the trained and tested network refers to the database with a defined range of input sludge load from 75 to 10,000 tons/year and the option of using an external company for sludge transport to the regional waste management center. The prepared database contains a total of 149,760 scenarios, of which 119,808 (80%) were used to train the NN, and the remaining 29,952 (20%) scenarios were used to test the NN.

Again, the grouping of the tested values was based on the difference to the actual NPV.

Of the total number of cases tested, all 29,952 (100%) have an accuracy of more than 95% (Table 5, Figure 14). The analysis results of the database therefore indicate a very high accuracy and reliability of the NN model.

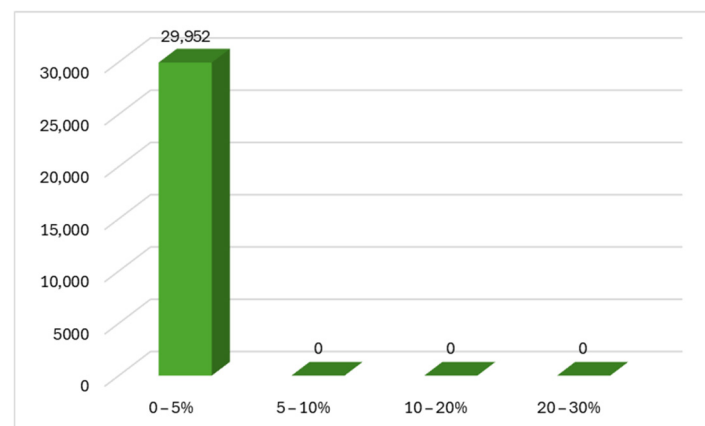
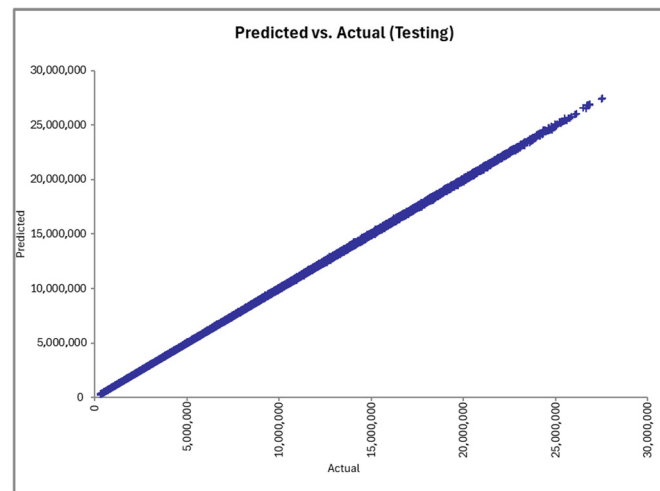


Figure 14. The number of tested cases in relation to the error tolerance of the trained and actual values (NN model 1.3).

Table 5. Statistical accuracy analysis for trained and tested network (NN model 1.3).

Linear Predictor vs. Neural Net		
Parameter	Linear Predictor	Neural Net
R-Square (Training)	0.9736	-
Root Mean Sq. Error (Training)	882,143.69	25,499.70
Root Mean Sq. Error (Testing)	880,471.28	51,071.37

Figure 15 shows the scatter plot between the actual and tested values. The results show a very high accuracy of the model.

**Figure 15.** Predicted vs. actual values (Testing) (NN model 1.3).

3.4. Trained Input Load Base from 10,000 to 20,000 Tons/Year, with the Involvement of an External Company for the Transport of SS to the Regional Center (NN Model No. 1.4)

In this scenario as well, of the total number of cases tested, all 29,952 (100%) have an accuracy of more than 95% (Table 6, Figure 16).

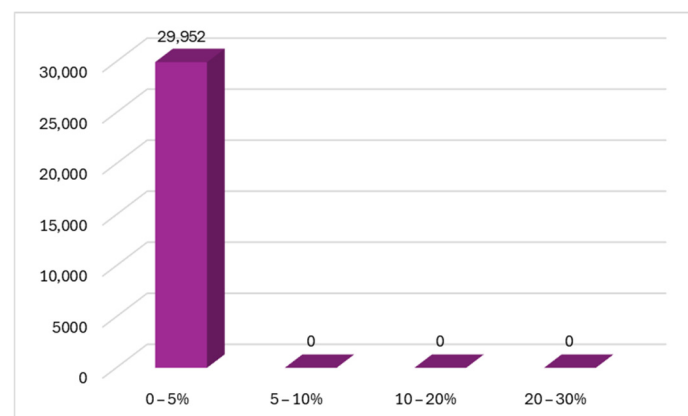
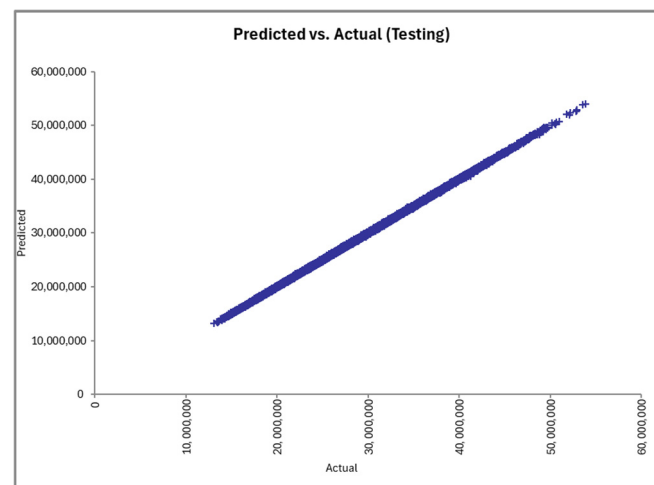
**Figure 16.** The number of tested cases in relation to the error tolerance of the trained and actual values (NN model 1.4).

Table 6. Statistical Accuracy Analysis for trained and tested network (NN model 1.4).

Linear Predictor vs. Neural Net		
Parameter	Linear Predictor	Neural Net
R-Square (Training)	0.9621	-
Root Mean Sq. Error (Training)	1,283,923.01	71,933.12
Root Mean Sq. Error (Testing)	1,285,954.00	135,988.87

Figure 17 shows the scatter plot between the actual and tested values. The results indicate a very high accuracy of the model, as all values lie in the narrow range along the $y = x$ diagonal.

**Figure 17.** Predicted vs. actual values (Testing) (NN model 1.4).

3.5. Trained Database with Handing over Dried SS to Another Legal Entity (NN Model No. 2)

The model of the trained and tested network refers to the database with the transport of dried SS to another legal entity for further treatment or disposal. Compared to the previous databases, this one is slightly smaller and contains a total of 74,880 scenarios, of which 59,904 (80%) were used to train the NN. The remaining 14,976 (20%) scenarios were used to test the NN.

The grouping of the tested values was based on the difference to the actual net present value (NPV).

Of the total number of cases tested, all 14,976 (100%) have an accuracy of more than 95% (Table 7, Figure 18). The analysis results of the database thus indicate a very high accuracy and reliability of the NN model.

Table 7. Statistical accuracy analysis for trained and tested network (NN model 2).

Linear Predictor vs. Neural Net		
Parameter	Linear Predictor	Neural Net
R-Square (Training)	0.9813	-
Root Mean Sq. Error (Training)	1,348,860.42	92,391.06
Root Mean Sq. Error (Testing)	1,335,075.66	120,533.72

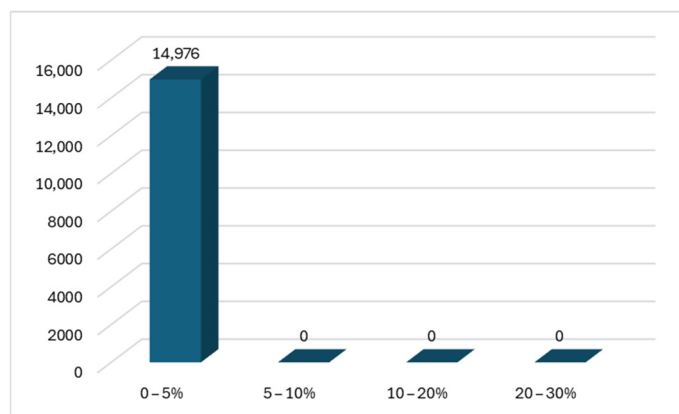


Figure 18. The number of tested cases in relation to the error tolerance of the trained and actual values (NN model 2).

Figure 19 shows the error histogram for the trained part of the NN. Looking at the absolute error values, a rather narrow and centered distribution around zero can also be observed in this case, which indicates a high accuracy of the model.

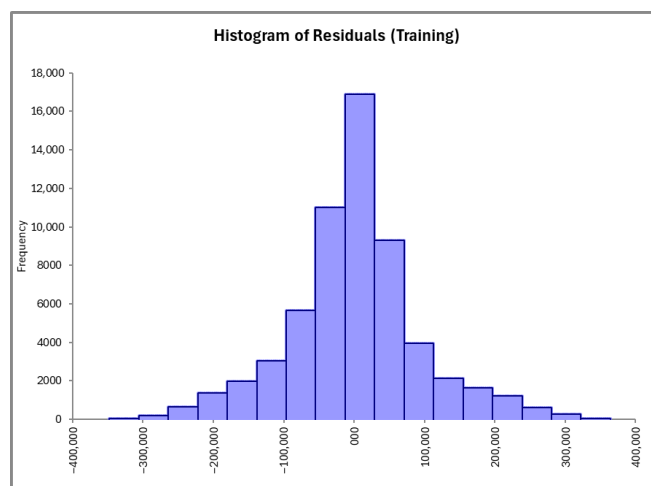


Figure 19. Histogram of residuals (Training) (NN model 2).

The scatter plot between the actual and tested values is shown in Figure 20. The results also show a very high accuracy of the model in this case.

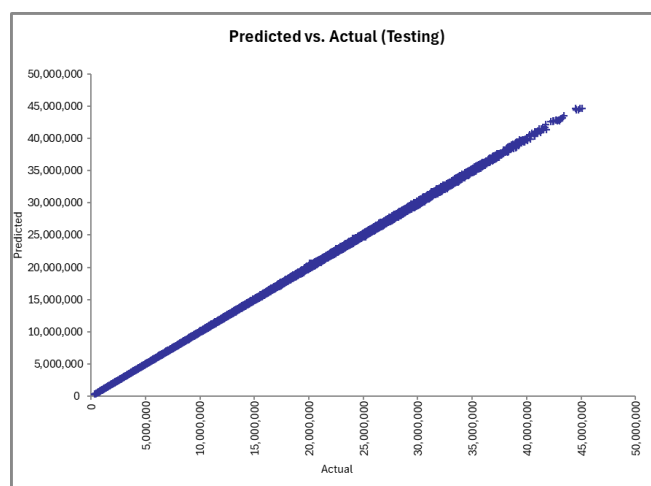


Figure 20. Predicted vs. actual values (Testing) (NN model 2).

4. Demonstration of the Developed Expert System Functionality and Discussion

Based on the results obtained by processing the previously tested and trained NNs, NPV curves of the total costs for the construction of SS solar drying facility were developed. Due to the extremely large number of possible combinations of input variables (input load, dry matter content in dewatered SS, dry matter content in dried SS, climate region, soil category, unit load, type of cover structure, sludge handling method, air treatment, air exchange method, distance of the plant from the regional center, sludge transport method), this paper presents scenarios with NPV curves in which the following variables were varied:

- Input load: ranges from 75 to 20,000 t/year;
- Distance of the facility from the regional center: <30 km, 30–60 km, 60–100 km, >100 km;
- Sludge transport method: own transport or contracted external company;

While the following input (independent) variables were kept constant with values:

- Dry matter content in dewatered SS: 25%;
- Dry matter content in dried SS: 90%;
- Climatic region: climate type Cfb;
- Soil category: type C;
- Unit load (dead load + wind + snow): 0.5–1.5 kN/m²;
- Type of cover structure: polycarbonate sheets;
- Sludge handling method: automated system;
- Air treatment: NO.
- Air exchange method: forced air exchange.

Costs (negative values) were defined as investment, operating, maintenance, depreciation and SS disposal costs. The revenues (positive values) were defined as the avoided costs for the treatment and disposal of the dewatered SS. The calculation was carried out for a period of 30 years with a discount rate of 4% (according to the Guide to Cost–Benefit Analysis of Investment Projects—Economic appraisal tool for Cohesion Policy 2014–2020) [56].

Figure 21 shows the NPV curves of the total costs for the SS solar drying facility with the option of own transport of the SS to the regional center, for four distance variants (up to 30 km, 30 to 60 km, 60 to 100 km, and over 100 km).

In the case of own transport of the dried SS to the regional center at a distance of <30 km, the NPV of the total costs for the SS solar drying facility becomes positive at an input load of 1000 tons/year of dewatered SS, which corresponds to a capacity of approximately 14,000 PE. This means that for all input loads below 1000 t/year and for the previously defined values of the other input variables, the investment in a SS solar drying facility is not economical. In such cases, the more cost-effective option is treatment and disposal of dewatered SS. An input load of 1000 t/year in this case represents a threshold point above which the option of constructing a SS solar drying facility becomes economically viable.

In the case of own transport of the dried SS to the regional center at a distance of 30 to 60 km, the NPV of the total costs for the SS solar drying facility becomes positive at an input load of 750 tons/year of dewatered SS, which corresponds to a capacity of approximately 10,000 PE.

In the case of own transport of the dried SS to the regional center at a distance of 60 to 100 km, the NPV of the total costs for the SS solar drying facility becomes positive at an input load of 500 tons/year of dewatered SS, which corresponds to a capacity of approximately 7000 PE.

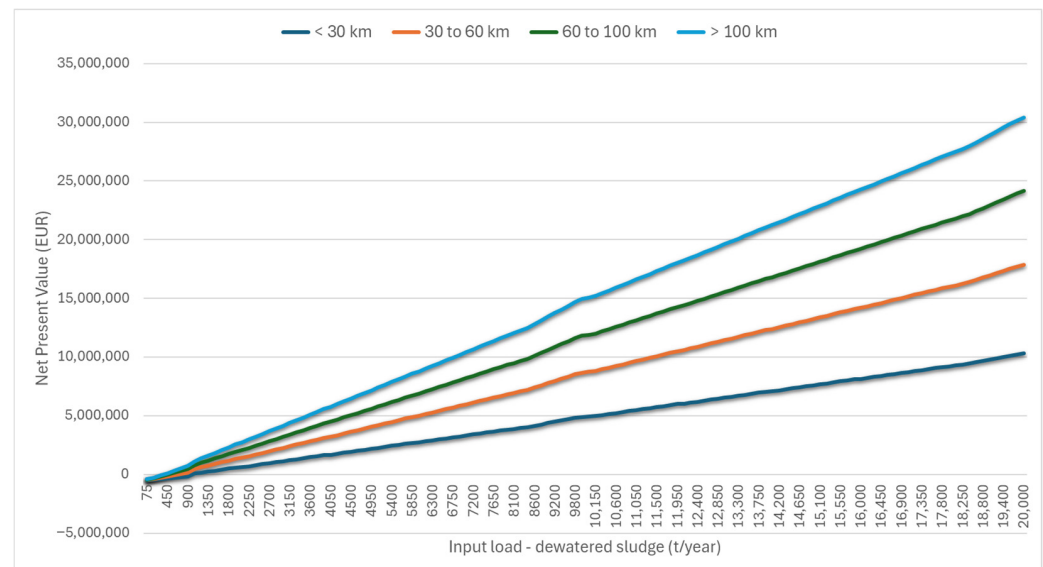


Figure 21. Net present value (NPV) depending on input load and for the scenario of own transport and disposal of dried SS at the regional center.

In the case of own transport of the dried SS to the regional center at a distance of >100 km, the NPV of the total costs for the SS solar drying facility becomes positive at an input load of 400 tons/year of dewatered SS, which corresponds to a capacity of approximately 5000 PE.

It is evident from the results that the option of investing in SS solar drying facility becomes increasingly cost-effective with higher input sludge loads, as well as with greater distances to the disposal site.

The second option relates to hiring an external company to transport the dried SS to the regional center.

Figure 22 shows the NPV curves of the total costs for the SS solar drying facility with the option of hiring an external company to transport the dried SS to the regional center, for four distance variants (up to 30 km, 30 to 60 km, 60 to 100 km, and over 100 km).

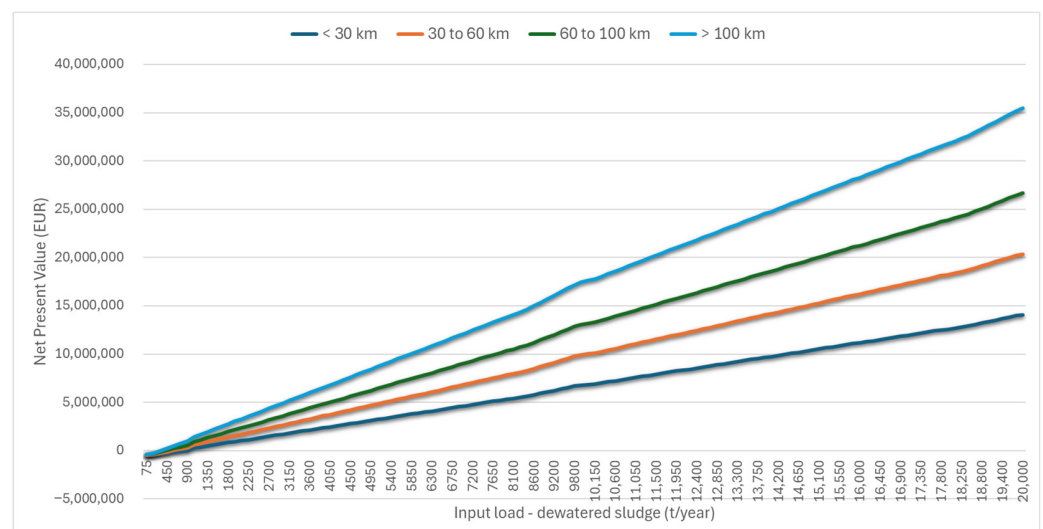


Figure 22. Net present value (NPV) depending on input load and for the scenario of engaging an external company for transport and disposal of dried SS at the regional center.

In the case of contracting an external company to transport the dried SS to the regional center at a distance of <30 km, the NPV of the total costs for the SS solar drying facility

becomes positive at an input load of 900 tons/year of dewatered SS, which corresponds to a capacity of about 12,000 PE.

If an external company is commissioned to transport the dried SS to the regional center 30 to 60 km away, the NPV of the total costs for the SS solar drying facility becomes positive with an input load of 600 tons/year of dewatered SS, which corresponds to a capacity of approximately 8000 PE.

If an external company is commissioned to transport the dried SS to the regional center 60 to 100 km away, the NPV of the total costs for the SS solar drying facility becomes positive with an input load of 450 tons/year of dewatered SS, which corresponds to a capacity of approximately 6000 PE.

In the case of hiring an external company to transport the dried SS to the regional center at a distance of >100 km, the NPV of the total costs for the SS solar drying facility becomes positive at an input load of 300 tons/year of dewatered SS, which corresponds to a capacity of about 4000 PE.

The third option refers to the calculation of the NPV of the total costs for the SS solar drying facility with the option of handing over of SS to another legal entity for further treatment and/or disposal, as shown in Figure 23.

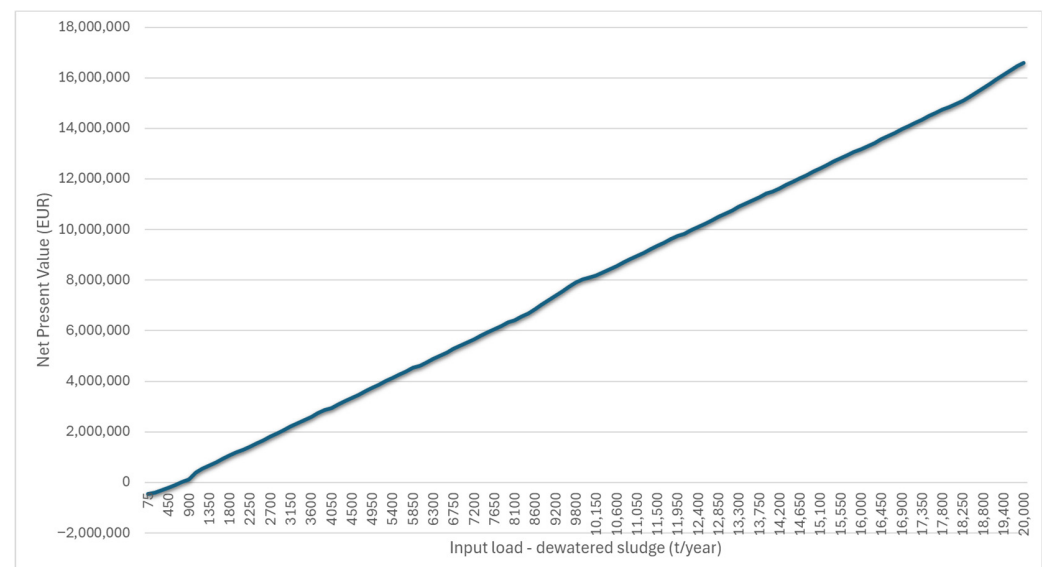


Figure 23. NPV curve for the option of handing over of dried SS to another legal entity for disposal.

Costs (negative values) were defined as investment, operation and maintenance, depreciation and the cost of transporting the SS to another legal entity. The costs of transporting the dewatered SS to another legal entity were recognized as revenue (positive values).

Figure 23 shows that the NPV in this case becomes positive at an input load of 750 tons/year of dewatered SS, which corresponds to a capacity of around 10,000 PE.

In order to ensure consistency in the evaluation of the results, a Variable Impact Analysis was also carried out. This method is used to assess the sensitivity of the NN predictions to changes in the values of independent (input) variables. The result of the analysis is the assignment of the Relative Variable Impact, expressed as a percentage, where the sum of all values equals 100%. The lower the percentage value assigned to a particular variable, the lower its influence on the prediction of the NN. In other words, a variable with a low impact value contributes only to a limited extent to the overall accuracy of the model and can be excluded from further analysis, especially if new, potentially more significant variables are expected to be included. However, it is important to note that a relative impact does not imply absolute irrelevance of a variable. For example, if one

variable has an impact of 99% and another of 1%, this clearly indicates the dominance of the first variable but does not exclude the relevance of the second variable, especially in the context of achieving high model accuracy, where even a small contribution may be significant.

In this study, a sensitivity analysis was conducted for all categorical and numerical input variables used in the development of the five NN models. The results showed that one variable, namely SS input load, had significantly higher influence than the others. Depending on the specific NN model, its influence ranged from 48% to 82%. It is noteworthy that its influence tended to decrease in the models characterized by higher values for the input load (NN models 1.2 and 1.4). A significant influence was also attributed to the variables distance of the SS solar drying facility from the regional center, air treatment and climate type in all five NN models. It should be emphasized that the variable sludge transport method was not varied in any of the first four NN models, as it was defined as a constant value in each case (decision for own transport or outsourcing to an external company). Similarly, in the case of NN model 2, the variable distance from the regional center was excluded from the analysis as this model assumes the handing over the SS to another legal entity for treatment and disposal.

Consequently, the NPV calculations presented above refer to scenarios that include a variation in SS input load and distance from the regional center, which were identified as the two most influential variables. Figure 24 shows a graphical representation of all input variables together with their relative influence on the five trained NNs.

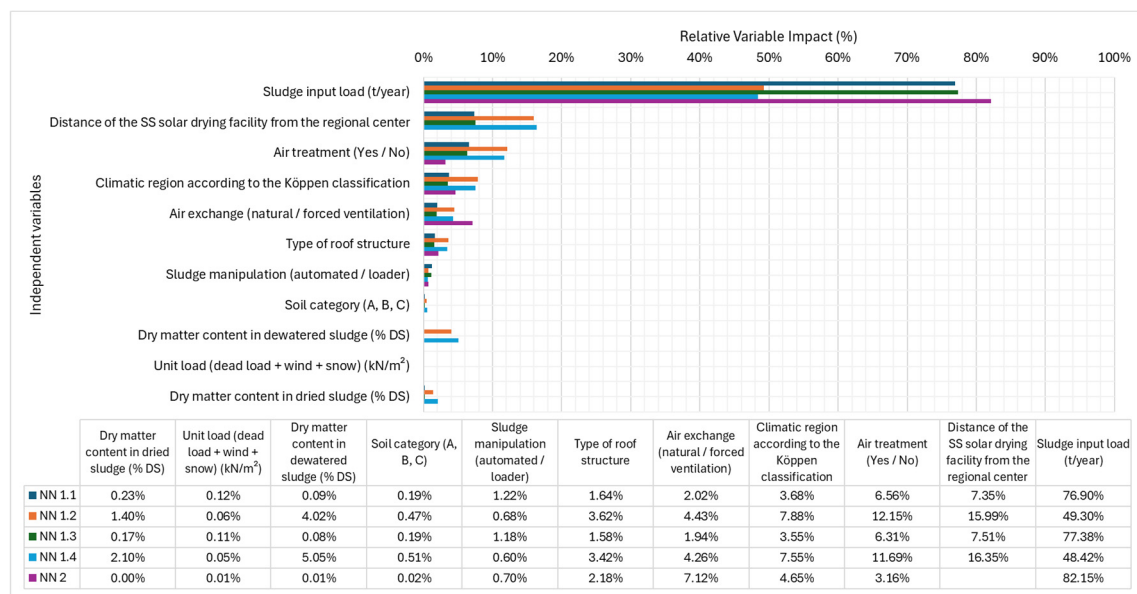


Figure 24. Relative variable impacts.

The results presented in this study provide a solid basis for decision-making on the economic feasibility of constructing an SS solar drying facility under the given assumptions. At the same time, the developed expert system, based on NNs, allows the application across a much wider range of input parameters (including location), which is the main advantage of this research. This is particularly important considering that there are no similar studies on a global scale addressing the economic feasibility of SS solar drying facilities. Some individual papers directly related to this topic [13,31,37] were published more than ten years ago and do not provide comprehensive tools for comparing economics of constructing an SS solar drying facility with alternative options for further treatment and/or disposal of dewatered SS.

5. Conclusions

This paper describes an expert system developed on the basis of sophisticated mathematical and computational tools such as NNs. It can calculate the economic feasibility of building a SS solar drying facility very quickly and efficiently, considering all relevant factors (influencing variables). It has potential practical use as it enables public water utilities, as well as other stakeholders (local government units, ministries, designers, other experts, etc.), to make better decisions regarding SS management.

The database used for the training and testing of the NN was created by manual data entry in MS Excel. It is based on a large number of real and hypothetical cases (scenarios) with different independent variables: input load, dry matter content in dewatered SS, dry matter content in dried SS, climatic region, soil category, unit load, type of cover structure, SS handling method, air treatment, air exchange method, distance of the facility from regional center, and SS transport method. In order to make it suitable for training and testing the NN, it was necessary to optimize the database to a manageable number of independent variables while ensuring the highest possible accuracy of the trained network. Based on sensitivity analyses of individual independent variables over a large number of iterations and numerous generated NNs, the database was restructured by narrowing down and adjusting the set of variables in order to optimize NN performance. Ultimately, a database with a total of 673,921 scenarios was created. Due to the large number of scenarios, the dataset was split into five smaller databases: four of them were of equal size (each containing 149,760 scenarios) and were subdivided according to the range of input load (from 75 to 10,000 t/year and from 10,000 to 20,000 t/year) and the type of SS transport to the regional center (own transport vs. outsourced company). The fifth database related to the option of handing over SS to another legal entity for further treatment and/or disposal and included 74,881 scenarios.

According to the results obtained, the NN showed a high accuracy in all cases, which ultimately enabled the calculation of the NPV of constructing a SS solar drying facility depending on the input load, the mode of transport and the distance to the final disposal site including the variation in all other variables. Another major advantage of the developed NNs is their flexibility in application under different circumstances, i.e., varying market conditions, which ensures their long-term usability even if market conditions change. Among the factors investigated, the SS input load and the distance between the solar drying facility and the regional center for subsequent treatment and/or disposal were identified as the most influential variables.

Regardless of the results obtained and presented in this research, there is room for further improvement of the expert system in the future. The focus of this paper was on the classic solar drying system, which relies solely on solar radiation to meet its energy needs. In recent years, however, there has been increasing interest in hybrid models of solar drying facilities, which, in addition to primary solar energy and the “greenhouse effect”, also utilize other forms of energy. This additional energy can come from photovoltaic collectors or from biogas energy generated by the anaerobic digestion of SS in the form of underfloor heating or direct introduction of warm air into the drying hall. This approach can further increase the economic efficiency of SS solar drying technology and make it attractive in regions with unfavorable climatic conditions.

In this context, it would be useful in future research to expand the database to include hybrid drying systems. It must be ensured that these other forms of energy do not exceed 50% of the total energy requirement for SS drying, as this would result in solar drying losing its status as the primary drying method.

As the expert system presented in this study is currently limited to defining the economic component, further research and development should also focus on expanding

its scope to include environmental and social aspects, including greenhouse gas emissions, odor control, health risk reduction, and nutrient recovery.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/cleantechnol7040090/s1>.

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