

Supporting Renewables' Penetration in Remote Areas through the Transformation of Non-Powered Dams

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Keywords: energy autarky, remote areas' electrification, renewable energy sources (RES) penetration, solar photovoltaic systems (SPVS), small-scale hydropower (SHP)

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Supplying power to remote areas may be a challenge, even for those communities already connected to the main grid. Power is often transmitted from long distances, under adverse weather conditions, and with aged equipment. As a rule, modernizing grid infrastructure in such areas to make it more resilient faces certain financial limitations. Local distribution may face stability issues and disruptions through the year and—equally important—it cannot absorb significant amounts of locally-produced power. The European policy has underlined the importance of energy production in local level towards meeting energy security and climate targets. However, the current status of these areas makes the utilization of the local potential prohibitive. This study builds on the observation that in the vicinity of such mountainous areas, irrigation dams often cover different non energy-related needs (e.g., irrigation, drinking water). Transforming these dams to small-scale hydropower (SHP) facilities can have a twofold effect: it can enhance the local energy portfolio with a renewable energy source that can be regulated and managed. Moreover, hydropower can provide additional flexibility to the local system and through reservoir operation to allow the connection of additional solar photovoltaic capacities. The developed methodological approach was tested in remote communities of mountainous Greece, where an earth-fill dam provides irrigation water. The results show a significant increase of renewables' penetration and enhanced communities' electricity autarky.

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Article

Supporting Renewables' Penetration in Remote Areas through the Transformation of Non-Powered Dams

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Abstract: Supplying power to remote areas may be a challenge, even for those communities already connected to the main grid. Power is often transmitted from long distances, under adverse weather conditions, and with aged equipment. As a rule, modernizing grid infrastructure in such areas to make it more resilient faces certain financial limitations. Local distribution may face stability issues and disruptions through the year and—equally important—it cannot absorb significant amounts of locally-produced power. The European policy has underlined the importance of energy production in local level towards meeting energy security and climate targets. However, the current status of these areas makes the utilization of the local potential prohibitive. This study builds on the observation that in the vicinity of such mountainous areas, irrigation dams often cover different non energy-related needs (e.g., irrigation, drinking water). Transforming these dams to small-scale hydropower (SHP) facilities can have a twofold effect: it can enhance the local energy portfolio with a renewable energy source that can be regulated and managed. Moreover, hydropower can provide additional flexibility to the local system and through reservoir operation to allow the connection of additional solar photovoltaic capacities. The developed methodological approach was tested in remote communities of mountainous Greece, where an earth-fill dam provides irrigation water. The results show a significant increase of renewables' penetration and enhanced communities' electricity autarky.

Keywords: small-scale hydropower (SHP); solar photovoltaic systems (SPVS); renewable energy sources (RES) penetration; remote areas' electrification; energy autarky

1. Introduction

Renewable energy (RE) targets pave the path for continuously increasing the share of clean technologies in national energy portfolios [1]. The number of countries adopting national policies has significantly increased during the last decade. Thus, while only 43 countries had adopted RE targets in 2005, in mid-2015, 164 countries have set their relevant goals [2]. In late 2014, the European Union (EU) adopted the “2030 climate & energy framework” that predicts at least 27% share for RE of EU energy consumption, from the 20% that was the target of the “2020 climate and energy package”.

Naturally, the majority of the countries (150/164) have defined electricity targets, aiming at utilizing their solar, hydropower, wind, and biomass potential for power. Despite the diversity

between the various targets, it becomes clear that as the levels of renewable energy sources (RES) in power systems increase, their integration into existing—often aged—power systems will face several challenges. RES integration can be particularly complicated to grid-connected remote, mountainous areas. Power systems in such areas are often characterized by aged equipment, while local power production (e.g., rooftop solar photovoltaic (PV) systems) in combination with demand fluctuations may challenge the system's stability [3]. Under certain situations, the output of grid-connected solar PV systems may cause over-voltage problems [4]. Accordingly, regulations require PV systems to automatically disconnect as soon as the maximum voltage limit is exceeded [5]. This results in spilled electricity, a phenomenon also known as curtailment. Transmitting the locally-produced RE of remote areas to other places is generally not an option, because of their distance from cities and consumption hubs. Trying to avoid such complications, regulatory authorities usually set a threshold on the maximum power capacity of RES in these areas. This threshold is generally low in order to keep the system's stability on the safe side. Thus, although it is a straightforward measure, it hampers RES deployment and the exploitation of local energy sources. Renewables' deployment could significantly benefit from novel management strategies and practices. Recent research and development (R&D) efforts in the power sector have explored the various storage opportunities [6]. The field of electro-chemical technology and battery storage options has experienced unprecedented progress in supporting renewables' integration [5]. On a utility scale, pumped hydropower storage (PHS) remains the dominant electricity storage option, with its global power capacity installed reaching 144.5 GW [7]. Although research on the possible contribution of new storage technologies is sustained [8], research on the role of hydropower on future grids mainly focuses on large-scale systems (more than 15 MW) [7,9,10], or even continental scale [11]. As far as island grids are concerned, the recent example of El-Hierro island in Spain (where the output of a wind farm is balanced by a pumped storage hydropower station [12]) has attracted the attention of the scientific community. A similar system configuration is under development in Ikaria island, Greece [13].

The present study introduces an alternative approach, and suggests the transformation of those non-powered dams (NPDs) in remote areas to mini-scale hydropower facilities (power capacity of less than 1 MW). As shown in the following sections, this transformation creates the potential for a complementary operation of hydro and solar PV systems (SPVS) and supports the integration of RES capacities. Our aim is to explore the additional flexibility provided by the hydro through the management of available water resources. Moving a step further, we have developed a methodology to assess the additional flexibility, aiming at increasing RE-based production without violating the policy regulations in place.

The rationale builds on two observations. Firstly, NPDs are common in the study-areas, since they are used to collect and supply drinking and irrigation water. Furthermore hydropower is one of the most flexible sources of electricity production [14]. Among the various technologies, hydropower can provide flexibility and stability to power systems. It allows easier integration of variable generation through the effective flexibility and the additional value of storage. This is particularly valuable at the often obsolete grid infrastructure of rural areas. Thus, the aim is threefold:

- (i) to suggest the possible utilization of NPDs—a significant asset of remote areas;
- (ii) to develop a methodology that analyzes this approach and tests it on a case study;
- (iii) to take into account the demand parameter and its fluctuations over time.

2. Background

RES penetration in remote areas can be increased with the flexible operation of a dam transformed into a hydroelectric station. Adding a flexible power generation facility, such as mini-hydro, offers the opportunity to control water releases — and power production—according to the local demand. In that sense, mini-hydros' operation follows both the consumption patterns and produces electricity complementary to local SPVS output.

Enabling increased penetration of RES is in the core of the scientific interest [15]. On one hand, its importance lies in the necessity to move towards decarbonized and efficient systems. In remote areas, it also reduces dependence on centrally-operated systems and promotes a bottom-up approach tailored to the local needs. This enables the transition from centrally-managed conventional production that is transmitted over long distances to locally-produced, flexible, and clean power production that is better suited to local status. This approach puts system change at its center, promotes developments towards smart grid operations [16], and supports the energy autonomy of these areas [17].

2.1. Utilizing the Energy Potential at Non-Powered Dams

The term “NPD” defines water storage infrastructure constructed to serve functionalities other than electricity production (e.g., drinking water provision, supply to irrigation networks, flood mitigation, and recreation). Dam construction constitutes a significant part of the total cost of a hydropower station, and may reach up to 70% of its total cost [18]. Moreover, most of the environmental impacts related to hydropower are attributed to dams. Apart from the various disruptions during the construction period, dams alter the river hydrology, affect sediment transport, and obstruct fish migration. However, adding power to existing dams does not impose additional environmental impacts. Due to the negligible additional environmental impact, licensing is considerably faster. Moreover, their transformation can be achieved in a much shorter time frame than building a hydropower station from scratch. The addition of electro-mechanical equipment is generally a straightforward process.

Naturally, not all NPDs are suitable for transformation. Water availability and the height difference (hydraulic head) determine the available power potential. Local conditions and landscape may also exclude some locations. Still, some dams in mountain regions offer the option to yield even more hydraulic head than their actual height by developing a diversion penstock [19]. Overall, NPDs’ development is achievable with lower levelised cost of energy (LCOE), lower business risk, and with fewer development barriers related to licensing.

For this reason, the U.S. Department of Energy has implemented a survey to estimate the available potential [19]. Of the total 84,000 dams, the majority lack the required flow that would generate enough power to justify the required investment. However, almost 600 sites have a potential capacity greater than 1 MW, with many of them being located near consumption centers. In total, U.S. NPDs have a total power potential of 12 GW. A known example is a transformation at the Ohio River, where existing locks and dams facilitated the process. Accordingly, six NPDs owned by the U.S. Army Corps of Engineers have been transformed to stations with a total capacity of 400 MW. Apart from the case in Ohio, 25 projects with a total capacity exceeding 250 MW followed the policy adaptations resulted by the [19] report.

In the European context, a thorough assessment of the existing NPD potential has not been performed so far. According to the European Environment Agency (EEA), there are currently approximately 7000 large dams in Europe, and thousands of additional smaller dams. Thus, it is expected that a power potential exists in European NPDs. Figure 1 illustrates dams in the main European rivers. It appears that although the vast majority already produce power, there are numerous NPDs—especially in southern Europe. The possibility of transforming NPDs to pumped storage hydropower stations has also been examined in a recent study [20].

As far as smaller dams are concerned, a recent work [18] estimated the potential of sub-Saharan Africa NPDs at 250 MW, with most of it placed in South Africa. The possibility of transforming NPDs using hydro-kinetic technologies (Archimedean screw turbines) has also been studied in the UK context [21]. An economic feasibility study [22] of 49 NPDs in the Piedmont region, NC, U.S. with mini-scale power potential (1–168 kW) revealed that their transformation can be financially viable in net-metering schemes when electricity tariffs are not very low. In late 2012, the Metropolitan authority of Vancouver in Canada announced its commitment to a sustainable management of drinking water infrastructure, including the transformation of NPDs [23].

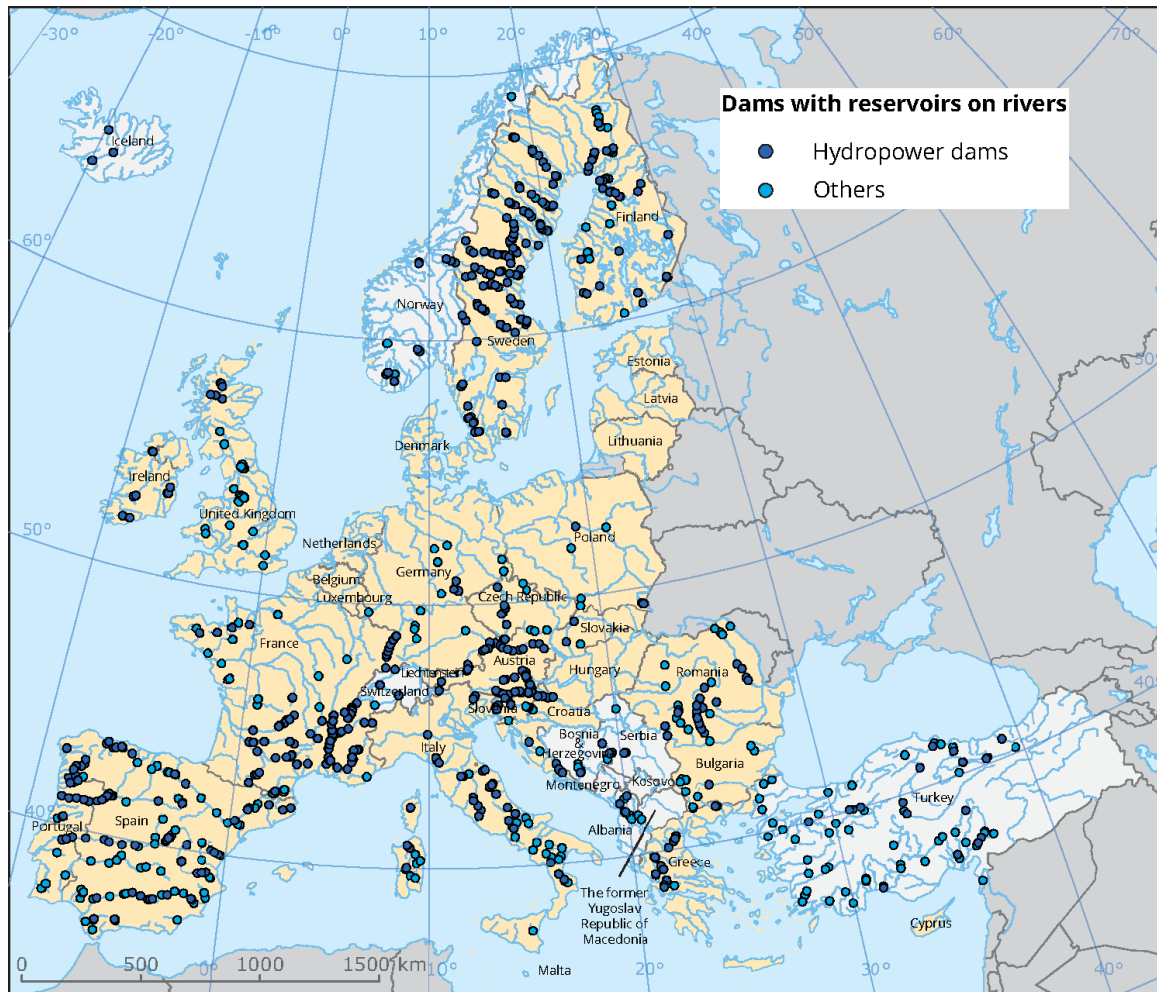


Figure 1. Dams on larger rivers in Europe. Hydropower stations and non-powered dams (NPDs). Source: European Environment Agency (EEA). Available online at: <http://www.eea.europa.eu/>.

2.2. Stabilizing the Existing Grid Infrastructure in Remote Areas

Development of the available hydropower potential allows electricity to be generated at the moment it is needed. Hydropower production can be planned according to demand, and respond to sudden peaks, providing large value to the system. Since variable RES require flexibility from other technologies, hydropower facilitates the integration of SPVS. This is also illustrated in national renewables' deployment strategies that utilize power exchange with neighboring countries hosting large hydropower capacities (e.g., Switzerland, Norway, Austria).

The operation of power systems benefits from flexible generation sources that can rapidly meet peak demands and maintain the system voltage levels. Hydropower plants (HPP) can inject power into the system faster than other energy sources. Hydropower has a rapid ramp rate (MW per minute) and responds by 50%–100% per minute, while combustion (10%–20% per minute) and coal units (1%–3% per minute) react considerably slower [24]. This feature also appears in small-scale hydropower plants (SHPs), and makes them appropriate for maintaining the balance between the electricity supply and demand.

Electricity system performance depends on stable frequency in the grid. HPPs instantaneously inject/absorb reactive power in order to control local transmission voltages [25]. Thus, HPPs help to maintain the power frequency, securing the stable operation of power systems.

2.3. Response to Consumption and Demand

Aged equipment combined with adverse weather conditions may result in black-outs in mountainous areas. In winter, weather often affects or even damages the transmission lines, resulting in outages. Temperature has been found to play an important role in the electricity load demand in Greece [26]. Thus, moderately high/low temperatures affect power consumption. In case the provider fails to transmit sufficient power, there are disruptions of service. Under the proposed scheme, the electricity provider benefits from the additional mini-hydro flexibility and reduces the transmitted power. Local production is enhanced, and local SPVS capacities may be increased further without violating policy limitations. The installation of solar panels on the face of the NPDs [27,28] is an additional option, especially when land is limited. Amplifying local production is particularly important in periods where demand reaches its peak on a national-level.

3. Application and Challenges

The proposed methodology has been designed and studied in a rural area in central Greece. Four settlements that are close to each other have been selected as a case study. The Lithaios river crosses this area, and an irrigation NPD is already in place. This dam is illustrated in Figure 2 along with the watershed and the hydrographic network. It has a maximum height of 32 m, a crest length of 526 m, and a total storage capacity of 2,500,000 m³. The collected water in the reservoir irrigates a cultivated area of \simeq 600 hectares.

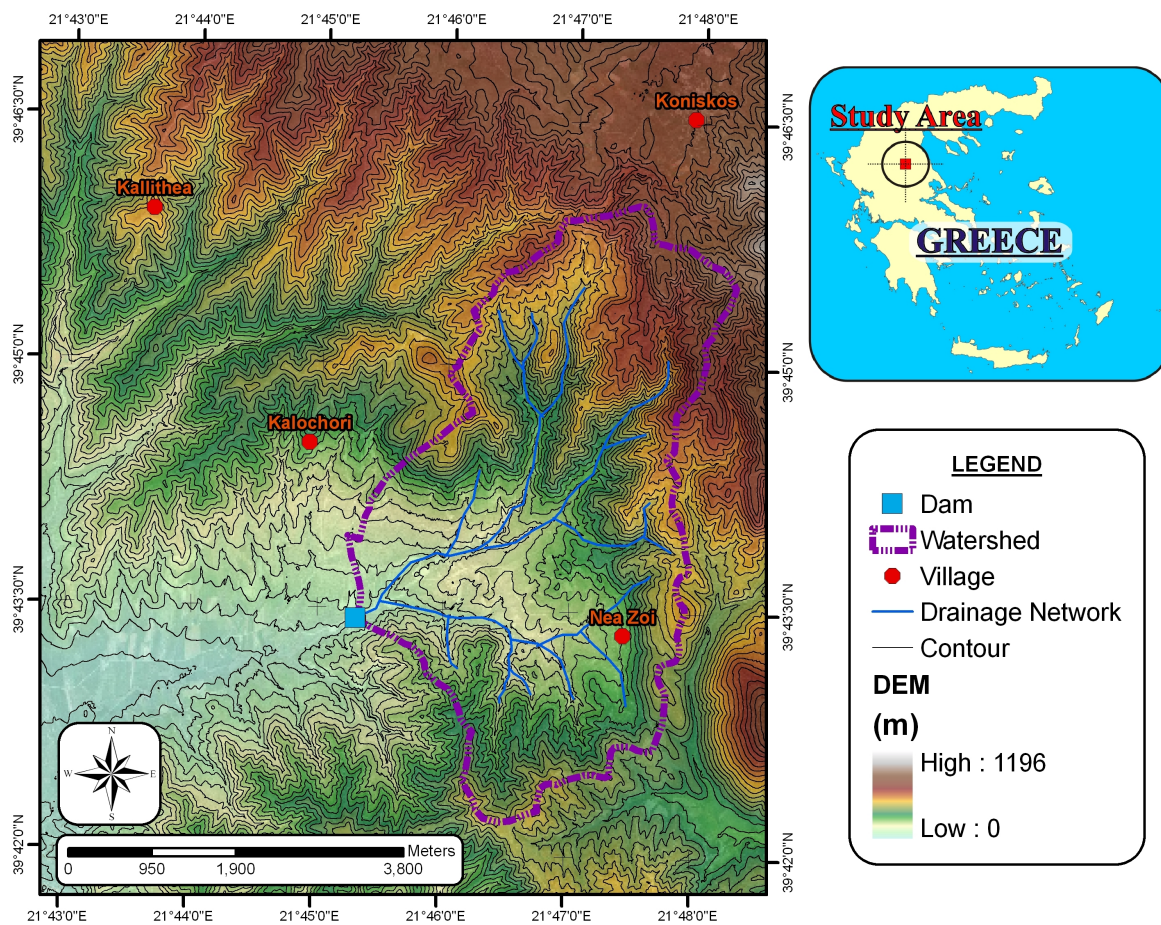


Figure 2. The study site: watershed, rivulet network, digital elevation model (DEM), dam and consumption points (villages).

3.1. Study Site

The present study examines the sustainable electrification of these mountainous settlements. These settlements are located in a high altitude ranging between 600 and 1000 m. Thus, access is an issue, and is only possible through a forest road. In total, there are approximately 100 dwellings, with the permanent population being 250 people. Although the selected villages are not tourist destinations, a small increase in the number of inhabitants appears in summer.

Local power production includes four identical rooftop SPVS that were recently installed, with an aggregated power capacity of 40 kWp. Moreover, a small wind system contributes additional 50 kW. The production of these systems is shown in Figure 3 (SPVS in green and wind in purple), and it currently covers $\approx 8.4\%$ of the total annual demand (shown in light red). The remaining power is provided by the central grid (in Figure 3, shown in dark red color). This is a low utilization rate of indigenous RES, and significantly lower than the threshold (30%) defined in the policy regulations [29] for RES' connections to the distribution network.

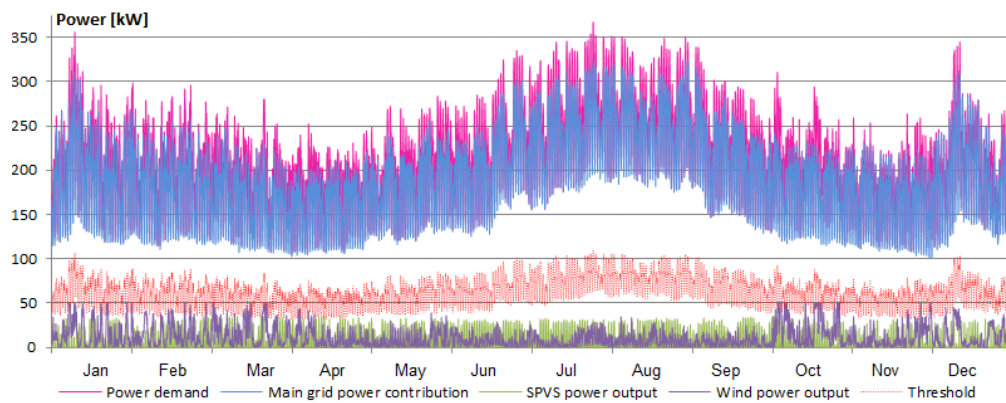


Figure 3. Power output from the various sources and demand. SPVS: solar photovoltaic systems.

3.2. Data Collection, Harmonization, and Analysis

Data on electricity consumption patterns were collected following an inquiry at the Hellenic Electricity Distribution Network Operator (HEDNO). HEDNO provided data with a 15-min time step that were further processed and harmonized. Average values were used in the analysis.

Hydrological information on river discharge were collected from the local prefecture. The same dataset was used when designing the dam construction project. Naturally, this data was already harmonized, corrected from outliers, and average values of several years' measurements were also provided. This information provided the hydropower output according to the—expected—technical characteristics of the hydropower station.

Wind data was locally collected using a typical wind mast installation. This data-collection process was implemented by one of the authors in collaboration with his previous employer, in terms of a corporate data collection project that covers the entire Greek territory. This data were harmonized and analyzed, with the results providing estimations of the power output of the small-scale wind systems installed in the settlements.

Solar PV output was produced through simulations using relevant software for the exact locations of all rooftop systems.

However, additional power capacities of RES cannot be connected without increasing the amounts of spilled energy. Currently, the installed RES need to be disconnected on a few occasions every year, due to excess of the 30% threshold. Thus, although clean technologies currently cover only a fraction of the demand, it is not possible to increase their capacities without spilling significant amounts of their power. This situation is illustrated in Figure 4, where a visualization of the collected data shows that in some occasions throughout the year, output of local RES exceeds the threshold. These occasions

appear exclusively in the first and last quarter of the year, which is the period between October and the end of March.

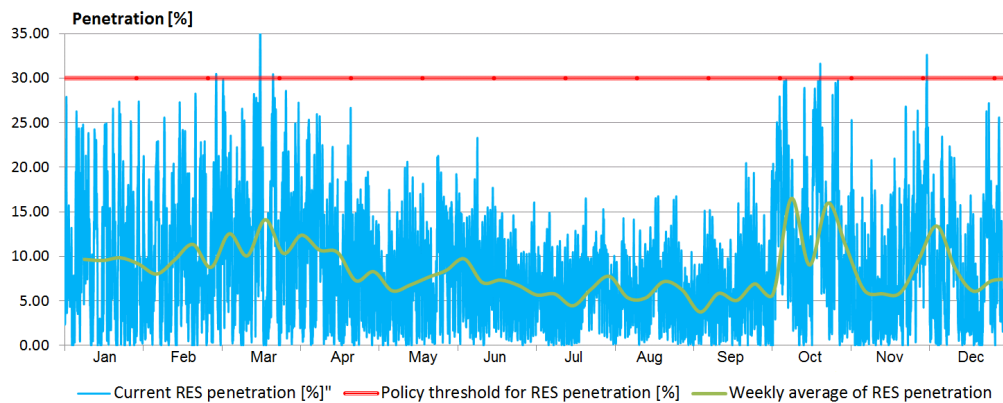


Figure 4. Current share of renewable energy sources (RES) in the final power consumption.

Comparing Figure 3 with Figure 4, it appears that the contribution of the RES is minimum when the demand increases. Thus, the small increase of population between June and August, that results in a clear increase of the demand, coincides with a lower power output from local PV and wind systems. In order to increase RES share, a possible option is “valley filling” yearly demand. This involves either shifting some of the demand to off-peak periods or storing electricity through “peak shaving” operations. Hydropower offers the opportunity for seasonal storage of energy through water storage and management. In those cases where irrigation and other water uses allow flexible operation, hydro-stations can fill their reservoir during low-demand months and provide more electricity in the high-demand season. This will result in “leveling” of the power the RES feed-in.

An additional challenge is related to some spikes appearing in the consumption curve (light red in Figure 3). These spikes appear suddenly due to unplanned energy-intensive activities, and require power injection from the grid. Such events increase pressure to the aged infrastructure that transmits power from large distances, with the nearest high-voltage sub-stations being approximately 50 km away. Filling the hydro-station’s reservoir allows for seasonal storage of the produced RE power and—equally important—in “peak shaving” of the RES output. The concept of “peak shaving” suggests the rollover of production from high-output periods (hill in Figure 5) to low-production periods (valley in Figure 5). This can be realized through seasonal water storage, and supports the overall system’s stability, also enabling further deployment of local RES.

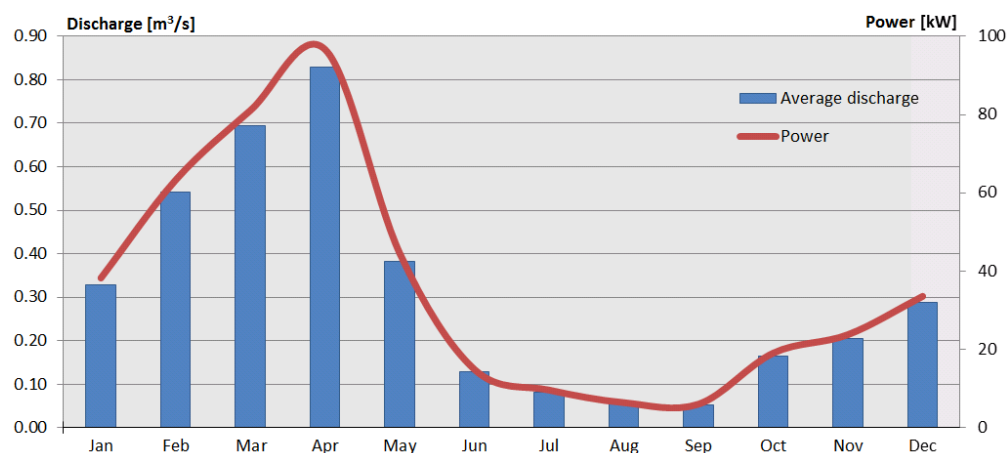


Figure 5. Average inflows to the NPD and estimated hydropower potential (no reservoir management).

3.3. Transformation of the Existing Non-Powered Dam

The NPD is already in place in the vicinity of the selected communities. Its main purpose is to store irrigation water and support the local agricultural production as well as to mitigate flood risk. The dam is placed in the run of a tributary that inflows into the reservoir. The discharge is continuous throughout the year, and its seasonal variations are typical Mediterranean. Thus, discharge has its maximum value during spring ($0.7\text{--}0.83\text{ m}^3/\text{s}$) mainly due to snow-melt, while in summer, the average flow becomes only minimal and ranges between 0.052 and $0.083\text{ m}^3/\text{s}$ (Figure 5, in blue).

The maximum dam height is 32 m , and its transformation to a hydropower station is expected to result in a hydroelectric facility with a lower hydraulic head. Using Equation (1), the available hydropower potential is estimated at approximately 100 kW . The red line in Figure 5 shows the average available power for every month, assuming a non-regulated run-of-river operation without reservoir management operations. Since all the factors of Equation (1) are either constant or have only small variations throughout the year (H), the maximum expected power (96.6 kW) appears in April, when average river flow reaches its maximum value.

$$P = n \times \rho \times g \times H \times Q \quad (1)$$

P : power (kW), n : dimensionless efficiency coefficient, ρ : water density (t/m^3) g : gravitational acceleration (m/s^2), H : hydraulic head (m), and Q : design water flow ($0.85\text{ m}^3/\text{s}$).

In order to utilize the available potential, a 100 kW turbine was selected. Cross-flow turbine type is the most suitable for this combination of discharge and hydraulic head [30]. Partitioned cross-flow turbines allow increased efficiency, even when the flow is less than 25% of the design flow. As shown in Figure 6, cross-flow turbines operate efficiently under different flow conditions using the arrangement for flow portioning. This unique characteristic is particularly useful in the present study, due to the average low summer flow.

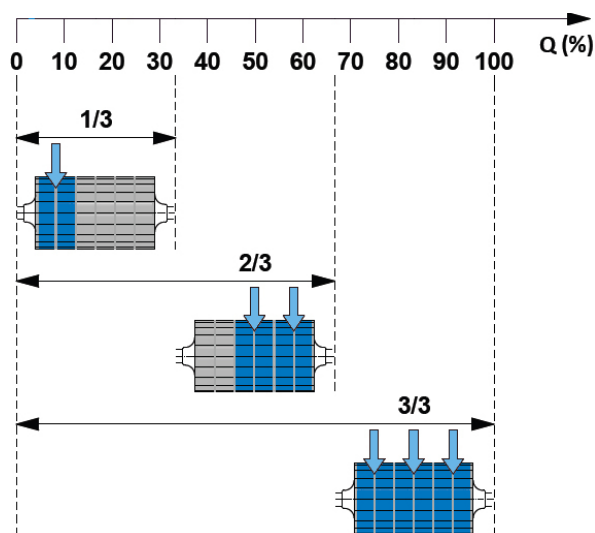


Figure 6. Cross-flow turbine: compartments and flexible operation.

3.4. Water and Energy Interrelation (Nexus)

Naturally, the transformation of the NPD should not affect the environmental flow regimes that secure the ecological conservation of the stream. Equally important is to ensure that powering the dam will not affect current services provided by the dam's operation. For this reason, the following paragraphs analyze the yearly operation characteristics of the dam.

The earth dam of the present analysis is constructed within the stream, and thus, the powerhouse will be built on the side of the river. The penstock feeding the turbine will be directly connected to the

existing irrigation network, and after producing electricity, water will flow downstream and feed the irrigation canal system. Its operation includes storing water in the high-flow period (December–May) and providing water for irrigation during summer. Currently, during the high-flow period, as soon as the reservoir is filled, inflow water is simply released into the stream. The dam’s transformation will utilize this potential that is currently wasted.

By simply operating the mini-hydro without applying reservoir management, summer hydropower electricity output will not be sufficient to fill the existing gap in production. This is due to the fact that high-flow period coincides with the period that RES penetration is already reaching the threshold. This challenge is illustrated in Figure 7, where it appears that the dam’s transformation will create additional “hills” (on top of the existing “hill”), and will result in further energy spill (excess to the 30% limit).

However, water resources management and intra-annual reservoir operation enable an optimization of the production that can reverse this challenge [31]. Such an intra-annual management can minimize the low-penetration “valley” of RES production (see Figure 4) by increasing summer hydropower production.

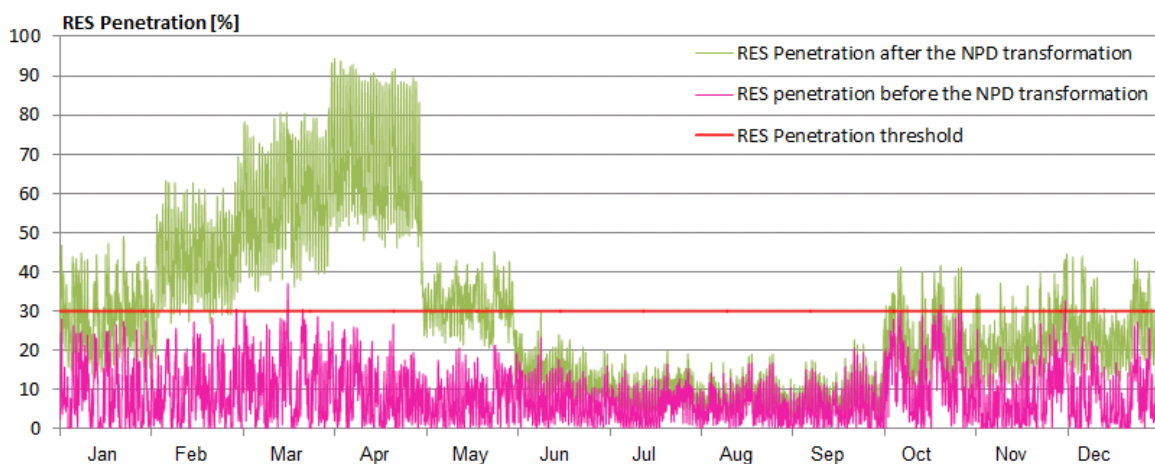


Figure 7. The penetration of RES with the hydro power added.

4. Proposed Approach: Optimized Reservoir Operation

An optimized operation of the reservoir not only allows the integration of the mini-hydro to the power system, but it also allows additional SPVS and/or wind deployment. Management practices will be based on information related to consumption collected in real-time.

4.1. Formation of the Optimization Model

The objective of the developed optimization model is to minimize the dependence on power availability of the main grid, as described in Equation (2). Moreover, an additional target is to maximize the overall share of RES in the final consumption (Equation (3)). These two objectives have a hierarchical nature; i.e., as soon as the conditions for the first objective are realized, the maximization of the second one takes place. Input data and results have been harmonized to an hourly resolution.

The constraints are presented in Equations (4)–(7), and include the policy threshold for the maximum penetration of RES at any time (Equation (4)). Moreover, they include requirements for the ecological conservation of both the rivulet and the reservoir. This is implemented by setting minimum requirements for the environment flow (EF) and the minimum water volume levels in the reservoir, as expressed in Equation (5). The stored water in the reservoir also needs to cover irrigation needs at any time, since this is the main purpose of the dam (Equation (6)). A constraint related to max reservoir levels aims provides basic flood risk management by avoiding unnecessary overflows (Equation (7)).

Objectives:

$$P^{grid} = \sum_{m=1}^{12} \sum_{d=1}^{30} \sum_{t=1}^{24} P_t \rightarrow \min \quad (2)$$

$$Output^{RES} = Output^{hydro} + Output^{PV} + Output^{wind} \rightarrow \max \quad (3)$$

Constraints:

$$Output^{RES} \leq 30\% \times Demand_t \quad (4)$$

$$EF_t \geq EF^{min}, \quad StoredWater_t \geq 25\% \times Capacity^{max} \quad (5)$$

$$IrrigationWater_t \geq IrrigationWater_t^{req} \quad (6)$$

$$StoredWater_t < Capacity^{max} \quad (7)$$

where P^{grid} is the maximum hourly power that is needed every month to be injected from the grid (kW); $Output^{RES, hydro, PV, wind}$ correspond to the electricity production of different resources (kWh); EF_t and EF^{min} are the actual and minimum required environmental flow values (m^3/s); $IrrigationWater_t$ and $IrrigationWater_t^{req}$ are the actual and required values for irrigation (m^3/s); $StoredWater_t$ is the amount of stored water in the reservoir (m^3).

As shown in Figure 6, the turbine can operate in three different modes that utilize the available potential, even when the flow is low. Moreover, the system responds instantaneously to the demand to cover possible peaks in demand. The first step of this exercise is to define a limit on the main grid's contribution. The objective function reaches its optimum when the grid contribution is 70% of the consumption and accordingly RES produce their maximum value, 30%. Considering that the maximum power demand is approximately 340 kW, the maximum power from the grid was set at 240 kW. Naturally, the remaining power will be covered by the SPVS, wind, and hydropower systems, with the latter playing the regulation role: it will increase/decrease its output according to demand.

Figure 8 shows the effect of this limit to the dependence on the grid. Setting this threshold results in a lower and more stable power dependence to the main grid, illustrated in red. Power from the grid in the current status is presented in green to enable comparison.

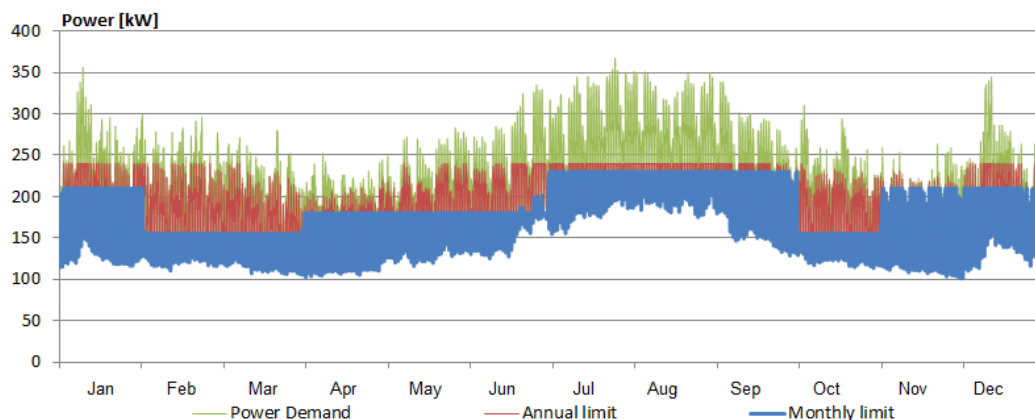


Figure 8. Demand and main grid contribution (annual and monthly limits).

In the second step, the maximum contribution from the main grid is determined on a monthly basis. Average monthly consumption can be divided in four categories, ranging from very low to very high. Each category contains three months, as shown in the following Table 1. Accordingly, monthly limits on the grid contribution (Figure 8, in blue) increase the RES potential further (difference between green and blue).

Table 1. Monthly power dependence to national grid supply.

| Demand | Very Low | Low | High | Very High |
|------------|------------------------------|----------------------|-----------------------------|---------------------------------|
| Power (kW) | 155 | 180 | 230 | 210 |
| Months | October February March | April May June | July August September | January November December |

4.2. Results

Taking these additional constraints into account, an Excel-based application was developed to optimize the operation of the mini-hydro. The results of this process are illustrated in Table 2, where the maximum hourly demand for power injection from the main grid is shown. This is equal to the peak power that the grid will be required to provide for four different cases: the current one without hydropower operation (No Hydro), when hydropower energy production is simply following the river flow also known as run-of-river (RoR) operation, when management practices set a yearly limitation to grid dependence (yearly management), and when these limitations are monthly (monthly management). It is interesting to note that although the addition of a run-of-river hydro (2nd case) naturally covers part of the electricity consumption, the monthly peak needs for instant power from the grid remain unchanged. Run-of-river hydropower provides base load electricity with such stations operating with no interruption apart from technical or environmental reasons. Due to their non-flexible operation, they cannot cover the “shoulder” or “peak” loads. Thus, although the NPD transformation contributes electricity to the local community, it fails to reduce dependency on the grid in terms of maximum instant power.

Table 2. Peak hourly power dependence from the grid for four different options (kW). No Hydro: without hydropower; ROR: run-of-river; and Manag.: management.

| Month | No Hydro | RoR | Yearly Manag. | Monthly Manag. |
|-----------|----------|--------|---------------|----------------|
| January | 196.1 | 196.1 | 125.3 | 96.1 |
| February | 147.0 | 147.0 | 129.6 | 47.0 |
| March | 141.3 | 141.3 | 134.0 | 54.0 |
| April | 117.2 | 117.2 | 117.2 | 77.4 |
| May | 139.3 | 139.3 | 123.9 | 63.9 |
| June | 176.3 | 176.3 | 114.8 | 95.5 |
| July | 168.1 | 168.1 | 85.3 | 75.3 |
| August | 150.4 | 150.4 | 65.1 | 55.1 |
| September | 187.8 | 187.8 | 111.4 | 101.4 |
| October | 128.7 | 128.7 | 126.4 | 51.2 |
| November | 130.3 | 130.3 | 130.3 | 109.0 |
| December | 207.9 | 207.9 | 138.6 | 108.6 |
| Sum | 1890.4 | 1890.4 | 1401.9 | 934.5 |

It appears that it is possible to reduce the grid requirement to half—from 1890.4 kW to 934.5 kW (49.4%)—when setting the monthly limits. Even when limiting the maximum power from the grid on an annual basis, a 25% reduction is achieved. It is interesting to note that transforming the NPD to mini-hydro without also providing the required management-control does not increase the electricity autarky, but slightly increases (+1.33%) the required power to be provided from the main grid.

The penetration of total RES also increases with the proposed method. Thus, while 8.4% of the total consumption was based on RES, the NPD transformation almost doubles this percentage,

resulting in 15% of RES penetration. This increase is illustrated in Figure 9, where it is obvious that the “valleys” of the RES penetration have been smoothed, and the “peak shaving” was effective.

Moreover, the authors estimated that the time complementarity between hydro and SPVS increased significantly with the presented methodology [32,33]. Thus, the correlation coefficient decreased from -0.20 to -0.74 , clearly indicating that hydro production is increased when SPVS output is minimum, and vice versa.

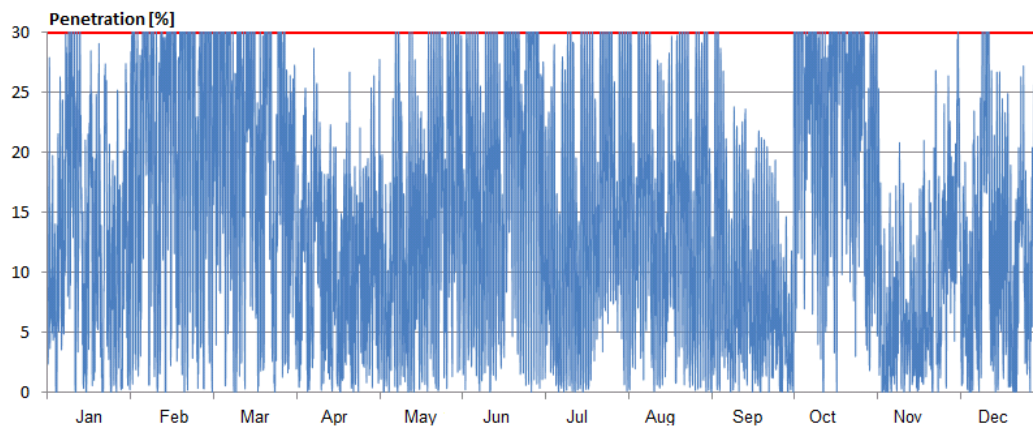


Figure 9. The penetration of RES following the optimized mini-hydro operation.

5. Conclusions

In this article, the use of already-existing infrastructure (NPDs) is demonstrated, suggesting the utilization of excess irrigation water to produce energy. The results show that the proposed approach can increase the penetration of RES in remote areas, where such irrigation schemes are common. Moreover, they increase the share of energy consumed in such rural areas coming from local energy production. This latter contribution is highlighted in EU energy policy and the defined climate targets.

Thus, the proposed approach has a twofold aim. On one hand, to support the environmentally-friendly mini-hydro development through the transformation of existing dams. This is particularly important in the EU context, where mini-hydro development has been stagnant in recent years. On the other hand hydropower development will support further developing other, variant RES and support grid stability.

The main advantage of this approach is that most of the infrastructure is already in place and the requirements in capital are between 30% and 50% of that for mini-hydro stations constructed from scratch. In addition, as the recent experience in rural electrification practices has shown, a mini-hydro can play a central role in moving further in terms of electricity autarky towards the new paradigm of electricity service.

Naturally, not all NPDs are suitable for transformation. Continuous and significant water flow is a prerequisite, while the hydraulic head is also a parameter of decisive importance. Still, the presented methodology can be applied to different areas to examine whether an NPD transformation is advantageous.

In a second phase, the optimization process can be applied to selected areas, taking into account different consumption patterns, different solar/wind/hydropower potential, as well as the financial parameter. Exploring the potential of battery storage to further support the proposed approach is expected to further increase renewables' penetration, and even allow the remote communities to fully cover their needs using indigenous resources through “smart grid” operations.

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Abbreviations

| | |
|-------|--|
| EEA | European Environment Agency |
| EF | Environment flow |
| EU | European Union |
| HEDNO | Hellenic Electricity Distribution Network Operator |
| HPP | Hydropower plant |
| LCOE | Levelised cost of energy |
| NPD | Non-powered dam |
| PHS | Pumped hydropower storage |
| PV | Photovoltaic |
| RE | Renewable energy |
| RES | Renewable energy sources |
| R&D | Research and development |
| SPVS | Solar photovoltaic system |
| SHP | Small-scale hydropower plant |

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