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<u>Diploma thesis</u>

Simulation framework for energy flows across multi-source power systems

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Πρόλογος

Γράφω αυτόν τον πρόλογο λίγες μόνο ημέρες πριν παρουσιάσω την διπλωματική μου εργασία – παράδοξο, ίσως, μα και κάπως αναμενόμενο. Πρώτα το ταξίδι, μετά η αφήγησή του. Το ταξίδι μου ως προπτυχιακή φοιτήτρια στη Σχολή Πολιτικών Μηχανικών του Εθνικού Μετσόβιου Πολυτεχνείου τελειώνει εδώ, με αυτή την ανασκόπηση που δεν θα μπορούσε να είναι τίποτα άλλο από μια εκδήλωση ευγνωμοσύνης σε όλους όσους συνέβαλαν για αυτό.

Αρχικά, θα ήθελα να ευχαριστήσω ιδιαίτερα τον κ. Ανδρέα Ευστρατιάδη, Αναπληρωτή Καθηγητή Ε.Μ.Π, για την επίβλεψη της παρούσας διπλωματικής εργασίας. Το έργο του «ΥΔΡΟΝΟΜΕΑΣ», άνοιξε για εμένα νέα μονοπάτια και μου έδωσε την ευκαιρία να συνδυάσω το γνωστικό αντικείμενο που σπουδάζω με την αγάπη μου για τον προγραμματισμό. Έτσι, από την πρώτη ιδέα μέχρι και την ολοκλήρωσή της, οι επιστημονικές του συμβουλές και υποδείξεις με καθοδήγησαν, με ενέπνευσαν, μου έδωσαν κίνητρο να συνεχίσω να προσπαθώ. Μα πάνω από όλα στάθηκε δίπλα μου ανθρώπινα, πίστεψε σε εμένα ακόμα και όταν δεν πίστευα εγώ η ίδια, κατανόησε τις βαθύτερες μου ανάγκες και με ενθάρρυνε ακόμα και στις πιο δύσκολες στιγμές.

Επίσης, θα ήθελα να ευχαριστήσω τον Υποψήφιο Διδάκτορα Θανάση Ζήσο, για την πολύτιμη συνεισφορά του. Διέθεσε αρκετό χρόνο για να μου καλύψει οποιαδήποτε απορία είχα, να βελτιώσει την διπλωματική μου, να με συμβουλεύσει και ήταν πάντα διαθέσιμος να μοιραστεί τις γνώσεις του. Τέλος, μου παραχώρησε απλόχερα τα απαραίτητα δεδομένα και η ερευνητική του δουλειά αποτέλεσε μια βάση για την παρούσα διπλωματική εργασία.

Οφείλω επίσης ένα μεγάλο «ευχαριστώ» στην Δρ. Τζωρτζίνα Σακκή, που με τις προτάσεις της, με ώθησε να κάνω βήματα μπροστά, να προσπαθήσω περισσότερο ανοίγοντας νέες πόρτες στην πορεία της διπλωματικής μου.

Δεν θα μπορούσα να μην πω ευχαριστώ στους γονείς μου, οι οποίοι στέκονται πάντα δίπλα μου, σε κάθε μου απόφαση και μου υπενθυμίζουν ότι πρέπει να κυνηγάω την ευτυχία μου, για την οποία φροντίζουν από την πρώτη ημέρα της ζωής μου. Τους χρωστάω κάθε μου επιτυχία.

Τέλος, θα ήθελα να ευχαριστήσω την παιδική μου φίλη Νικολέτα, με την οποία τα τελευταία είκοσι χρόνια κυνηγάμε τα όνειρά μας μαζί, αλλά και όλους μου τους φίλους που με υποστήριζαν όλον αυτό τον καιρό και άντεξαν να με ακούν να μιλάω για αυτή την διπλωματική με ενθουσιασμό και υπομονή.

Κολιούκου Αικατερίνη

Αθήνα, Μάρτιος 2025

Abstract

Hybrid renewable energy systems are becoming the norm as regard to electricity grids in Europe and Greece. However, the combination of renewable sources, conventional units and power storage components creates highly complicated systems, and, consequently, renders the need for advanced simulation – optimization tools to support both their planning and management. Building upon existing methodologies often used in water management problems, namely the network linear programming context (also referred to as transhipment problem), we attempt to solve the optimal energy flow problem, respecting the operational rules for all common components of hybrid renewable systems (solar P/V panels, wind turbines, small hydropower stations, thermal plants, pumped-storage units). In this vein, we establish a generic framework for calculating the energy production from each source and its allocation/storage across the grid. Emphasis is given to thermal unit's modelling which requires the introduction of an iterative procedure within simulation. The above are implemented within an integrated tool, called *Enerflow*, providing all the above features via a user – friendly graphic user interface. To test the newly developed tool, we apply it to the case of Sifnos, a Greek island not connected to mainland's electricity grid which aims to achieve energy independency until 2030. The outcomes of several simulations are compared and the impacts of changing basic design variables are examined.

Περίληψη

Τα υβριδικά συστήματα ανανεώσιμων πηγών ενέργειας γίνονται ο κανόνας όσον αφορά στα δίκτυα ηλεκτρικής ενέργειας στην Ευρώπη και την Ελλάδα. Ωστόσο, ο συνδυασμός ανανεώσιμων πηγών, συμβατικών μονάδων και στοιχείων αποθήκευσης ενέργειας δημιουργεί ιδιαίτερα πολύπλοκα συστήματα και, κατά συνέπεια, καθιστά αναγκαία την ύπαρξη προηγμένων εργαλείων προσομοίωσης - βελτιστοποίησης για την υποστήριξη τόσο του σχεδιασμού όσο και της διαχείρισής τους. Βασιζόμενοι σε υπάρχουσες μεθοδολογίες που χρησιμοποιούνται συχνά σε προβλήματα διαχείρισης υδάτων, συγκεκριμένα στο πλαίσιο του δικτυακού γραμμικού προγραμματισμού (που αναφέρεται και ως πρόβλημα μεταφόρτωσης), επιχειρούμε να επιλύσουμε το πρόβλημα της βέλτιστης ροής ενέργειας, τηρώντας τους κανόνες λειτουργίας για όλα τα συνήθη στοιχεία των υβριδικών συστημάτων ανανεώσιμων πηγών ενέργειας (Φ/Β πλαίσια, ανεμογεννήτριες, μικροί υδροηλεκτρικοί σταθμοί, θερμικές μονάδες, μονάδες αντλησιοταμίευσης). Σε αυτή τη λογική, δημιουργούμε ένα γενικό πλαίσιο για τον υπολογισμό της παραγωγής ενέργειας από κάθε πηγή και της κατανομής/αποθήκευσης της στο δίκτυο. Έμφαση δίνεται στον χειρισμό των θερμικών μονάδων που απαιτεί την εισαγωγή μιας επαναληπτικής διαδικασίας εντός της προσομοίωσης. Τα παραπάνω υλοποιούνται σε ένα ολοκληρωμένο εργαλείο, το οποίο ονομάζεται *Enerflow*, που παρέχει όλα τα παραπάνω χαρακτηριστικά μέσω ενός φιλικού προς το χρήστη γραφικού περιβάλλοντος. Για να δοκιμάσουμε το εργαλείο που αναπτύχθηκε, το εφαρμόζουμε στην περίπτωση της Σίφνου, ενός ελληνικού νησιού που δεν είναι συνδεδεμένο με το ηπειρωτικό δίκτυο ηλεκτρικής ενέργειας και το οποίο στοχεύει να επιτύχει ενεργειακή ανεξαρτησία έως το 2030. Τα αποτελέσματα των προσομοιώσεων συγκρίνονται, και εξετάζονται οι επιπτώσεις της αλλαγής βασικών μεγεθών σχεδιασμού.

Εκτενής περίληψη

Η παρούσα διπλωματική εργασία στοχεύει στην ανάπτυξη ενός λογισμικού βέλτιστης προσομοίωσης ροών ενέργειας σε ένα υβριδικό ενεργειακό σύστημα. Με τον όρο «ροές ενέργειας» εννοούμε την μεταφερόμενη ποσότητα ενέργειας μεταξύ κόμβων προσφοράς και ζήτησης. Η βέλτιστη προσομοίωση στοχεύει στη μείωση του κόστους, υπακούοντας πάντα σε τεχνικούς περιορισμούς και προτεραιότητες.

Τα τελευταία χρόνια η ανάγκη παρείσφρησης των ανανεώσιμων πηγών ενέργειας στο ενεργειακό μίγμα μιας χώρας κατέστη επιτακτικότερη. Η ενεργειακή κρίση του 2022, απόρροια γεωπολιτικών εξελίξεων, με κυριότερη αυτήν της εισβολής της Ρωσίας στην Ουκρανία, έφερε τους πολίτες της Ευρώπης αντιμέτωπους με υπέρογκους λογαριασμούς ρεύματος. Η ενεργειακή ανεξαρτητοποίηση της Γηραιάς Ηπείρου είναι πλέον μονόδρομος, και κατά συνέπεια τα υβριδικά ενεργειακά συστήματα αποτελούν την απάντηση.

Τα υβριδικά συστήματα συνήθως αποτελούνται από μίγμα ανανεώσιμων πηγών ενέργειας αλλά και μια συμβατική μονάδα παραγωγής ηλεκτρισμού, που λειτουργεί ως εφεδρεία σε περιπτώσεις ελλείμματος. Τα φωτοβολταϊκά, οι ανεμογεννήτριες, και τα μικρά υδροηλεκτρικά έργα είναι στοιχεία υβριδικού συστήματος, αρκετά δημοφιλή τα τελευταία χρόνια. Η αποθήκευση ενέργειας αποτελεί αδήριτη ανάγκη σε τέτοια συστήματα, με την αντλησιοταμίευση να αποτελεί έναν εκ των πλέον βιώσιμων μεθόδων διαχείρισης και αξιοποίησης διαθέσιμων πόρων.

Η εύρεση της βέλτιστης «διαδρομής» της ενέργειας βασίζεται στην λύση του προβλήματος δικτυακού γραμμικού προγραμματισμού (αναφέρεται και ως πρόβλημα μεταφόρτωσης), το οποίο στοχεύει στην ελαχιστοποίηση του κόστους μεταφοράς ποσότητας μέσω ενός δικτύου (γράφου). Η μητρωική διατύπωση του προβλήματος είναι η ακόλουθη:

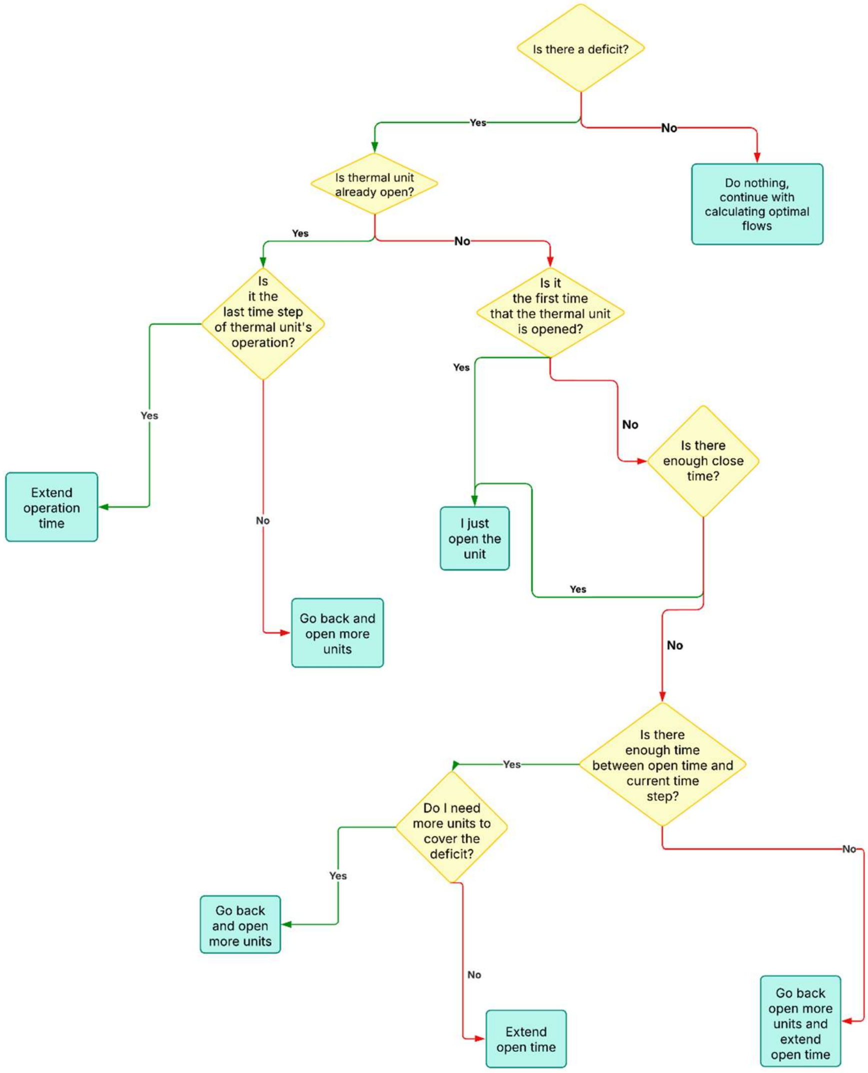
$$\begin{aligned} &minimise\ f(x) = c^T x \\ &έτσι\ ώστε\ A \times x = y \\ &0 \leq x \leq u \end{aligned}$$

όπου $\boldsymbol{x}$ το διάνυσμα των μεταφερόμενων ποσοτήτων, $\boldsymbol{c}$ το διάνυσμα κόστους, $\boldsymbol{A}$ το μητρώο πρόσπτωσης (αντιπροσωπευτικό της τοπολογίας του δικτύου), $\boldsymbol{y}$ το διάνυσμα προσφορών και ζήτησης και $\boldsymbol{u}$ το διάνυσμα χωρητικοτήτων.

Το *Enerflow* προσφέρει στον χρήστη ένα εύκολα κατανοήσιμο γραφικό περιβάλλον, στο οποίο μπορεί να δημιουργήσει το δικό του υβριδικό σύστημα αποτελούμενο από μίγμα στοιχείων παραγωγής ενέργειας. Πιο συγκεκριμένα, ο χρήστης εισάγει τα βασικά χαρακτηριστικά της πηγής ενέργειας, τα απαιτούμενα μετεωρολογικά δεδομένα και το λογισμικό υπολογίζει την ωριαία ενεργειακή παραγωγή. Για παράδειγμα για τα φωτοβολταϊκά πλαίσια, πρέπει να εισάγει τις ωριαίες χρονοσειρές θερμοκρασίας και ακτινοβολίας, τον αριθμό των πάνελ που χρησιμοποιούνται, τον θερμοκρασιακό συντελεστή, και τον μέγιστο βαθμό απόδοσης.

Αφού ο χρήστης κατασκευάσει το δίκτυο συνδέοντας τους κόμβους προσφοράς και ζήτησης και αναθέτοντας μια καθορισμένη τιμή κόστους προτεραιότητας, το λογισμικό συνεχίζει στην βέλτιστη προσομοίωση. Για την επίτευξή της, δημιουργείται ένα εικονικό δίκτυο στο οποίο προστίθεται ένας συσσωρευτικός κόμβος. Όλοι οι κόμβοι συνδέονται με τον συσσωρευτικό κόμβο με εικονικές παροχετευτικότητες, που εξαρτώνται από τις τιμές ζήτησης και προσφοράς. Πιο συγκεκριμένα, στην σύνδεση ενός κόμβου ζήτησης με έναν κόμβο προσφοράς, η μέγιστη παροχευτετικότητα θα είναι ίση με την ζήτηση, όταν συνδέεται ένας κόμβος προσφοράς με τον συσσωρευτικό κόμβο η παροχετευτικότητα είναι ίση με την προσφορά και, τέλος, στην σύνδεση μεταξύ ενός κόμβου ζήτησης με τον συσσωρευτικό κόμβο, η παροχετευτικότητα ισούται με την ζήτηση.

Όταν το υβριδικό σύστημα περιέχει και σύστημα αντλησοταμίευσης προστίθεται ακόμα ένας εικονικός κόμβος, αυτός της περίσσειας, όπου καταλήγουν οι περισσευούμενες ποσότητες των κόμβων προσφοράς (φορτίο προς απόρριψη). Μέσω αυτού του κόμβου, «αποφασίζεται» αν θα αντληθεί νερό (δηλαδή αν δύναται η αποθήκευση ενέργειας) ή αν θα αφεθεί νερό από τον πάνω ταμιευτήρα (δηλαδή αν απαιτείται παραγωγή ενέργειας). Ειδικότερα, αφού οι κόμβοι προσφοράς καλύψουν κάθε ζήτηση, αν υπάρχει περίσσεια, εκείνη μεταφέρεται στον αντίστοιχο κόμβο. Η περίσσεια μεταφράζεται σε όγκο νερού και εφόσον υπάρχει διαθέσιμη χωρητικότητα στον άνω ταμιευτήρα και διαθέσιμο απόθεμα στον κάτω, ο όγκος νερού αντλείται και η περίσσεια ενέργειας έχει πλέον αποθηκευτεί. Αν δεν υπάρχει περίσσεια ενέργειας, το σύστημα ταμιευτήρων λειτουργεί ως κόμβος προσφοράς, αφού όμως πρώτα ελεγχθούν τα αποθέματα νερού και η αντίστοιχη ενέργεια που μπορεί να παραχθεί. Με βάση το εικονικό δίκτυο, γίνεται η βέλτιστη προσομοίωση, θέτοντας τις μεταβλητές ελέγχου σε κάθε χρονικό βήμα.



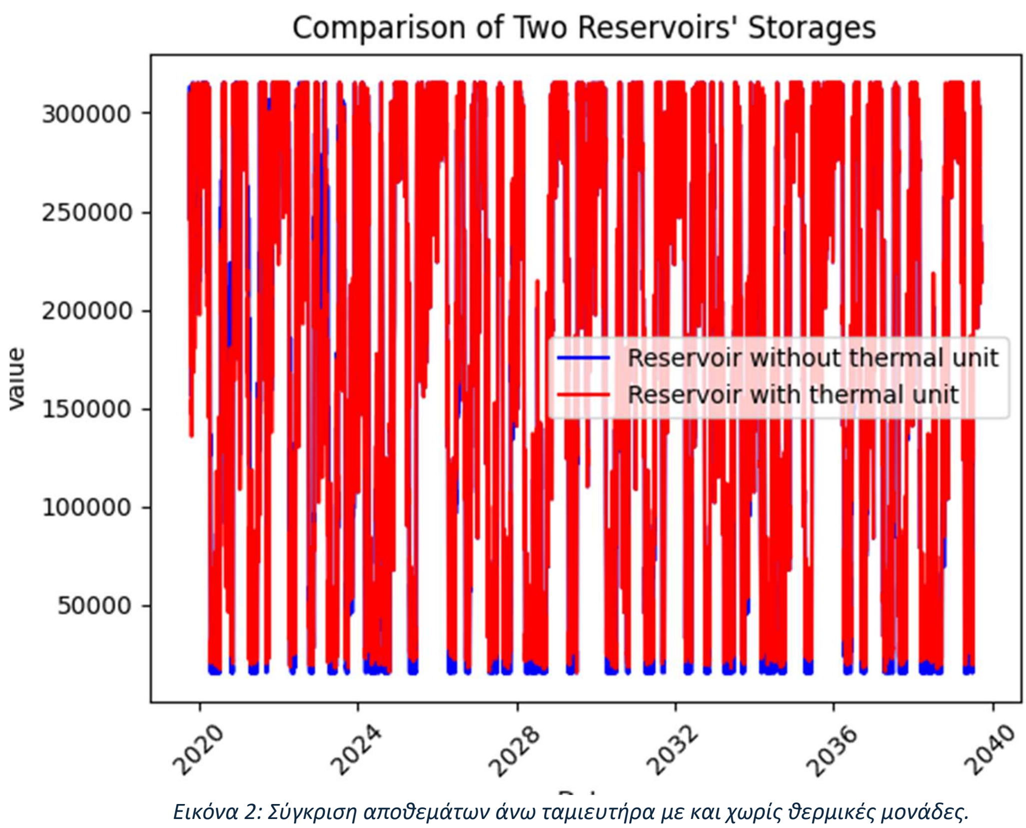
Εικόνα 1: Διάγραμμα ροής διαδικασίας λειτουργίας θερμικών μονάδων.

Η προσθήκη μιας συμβατικής γεννήτριας (π.χ., θερμική μονάδα) ως εφεδρεία στο σύστημα, περιπλέκει αρκετά το πρόβλημα. Η συμβατική μονάδα απαιτεί κάποιες ώρες για την ενεργοποίησή της και πρέπει να τηρείται υποχρεωτικά ένας ελάχιστος χρόνος που πρέπει να παραμείνει κλειστή.

Συνεπώς, οι έλεγχοι που πρέπει να γίνουν είναι πολλοί και η ακολουθείται μια επαναληπτική διαδικασία. Η πορεία που ακολουθείται, αποδίδεται στο διάγραμμα ροής της Εικόνας 1.

Το νησί της Σίφνου συνιστά ένα εύστοχο και αντιπροσωπευτικό παράδειγμα υβριδικού ενεργειακού συστήματος. Εκτελώντας διάφορες προσομοιώσεις οι Zisos et al. (2023) πρότειναν ένα σύστημα αποτελούμενο από τέσσερεις ανεμογεννήτριες ισχύος 2,4 MW, φωτοβολταικών και ένα σύστημα αντλησοταμίευσης αποτελούμενο από έναν άνω ταμιευτήρα, χωρητικότητας περίπου 315 000 m^3, με την θάλασσα να παίζει τον ρόλο του κάτω ταμιευτήρα. Με το συγκεκριμένο σύστημα είναι εφικτή η αποθήκευση ενέργειας, αντλώντας νερό από τον κάτω ταμιευτήρα και αφήνοντας νερό από τον άνω ταμιευτήρα σε περιόδους ελλείμματος. Το παράδειγμα της Σίφνου προσομοιώθηκε με και χωρίς την παρουσία των εννέα μονάδων συμβατικής πηγής ενέργειας 1,2 MW η κάθε μία.

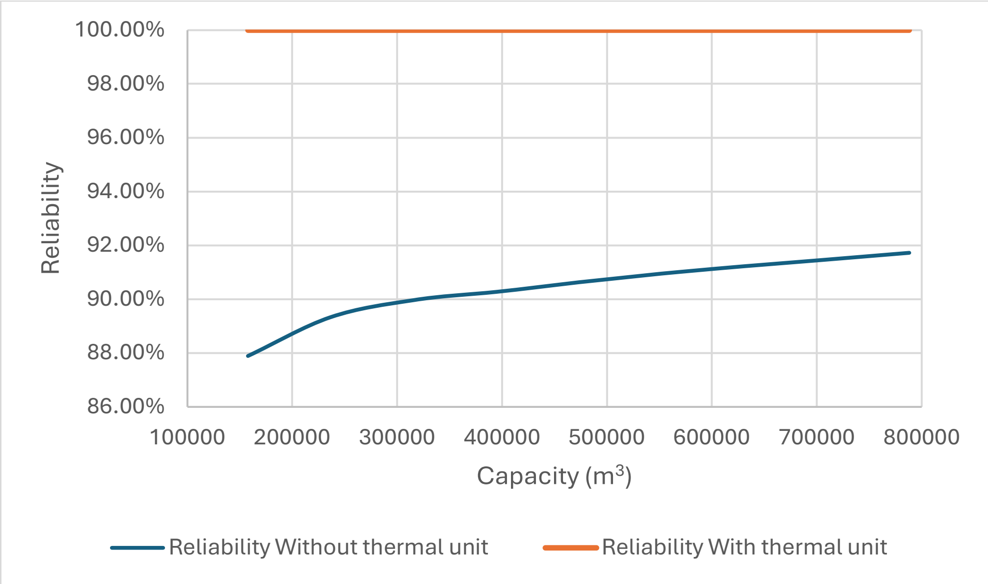
Συγκρίνοντας τα αποτελέσματα των προσομοιώσεων με θερμική μονάδα και χωρίς βλέπουμε ότι η αξιοπιστία αυξάνεται από το 90% στο 100% και είναι αξιοσημείωτο το γεγονός ότι τα αποθέματα των ταμιευτήρων στην δεύτερη περίπτωση κυμαίνονται σε υψηλότερες τιμές, καθώς οι θερμικές μονάδες λειτουργούν περισσότερο από όσο χρειάζεται (λόγω των λειτουργικών περιορισμών τους) και παρατηρούνται πολλές περίσσειες που αποθηκεύονται με την μορφή νερού.



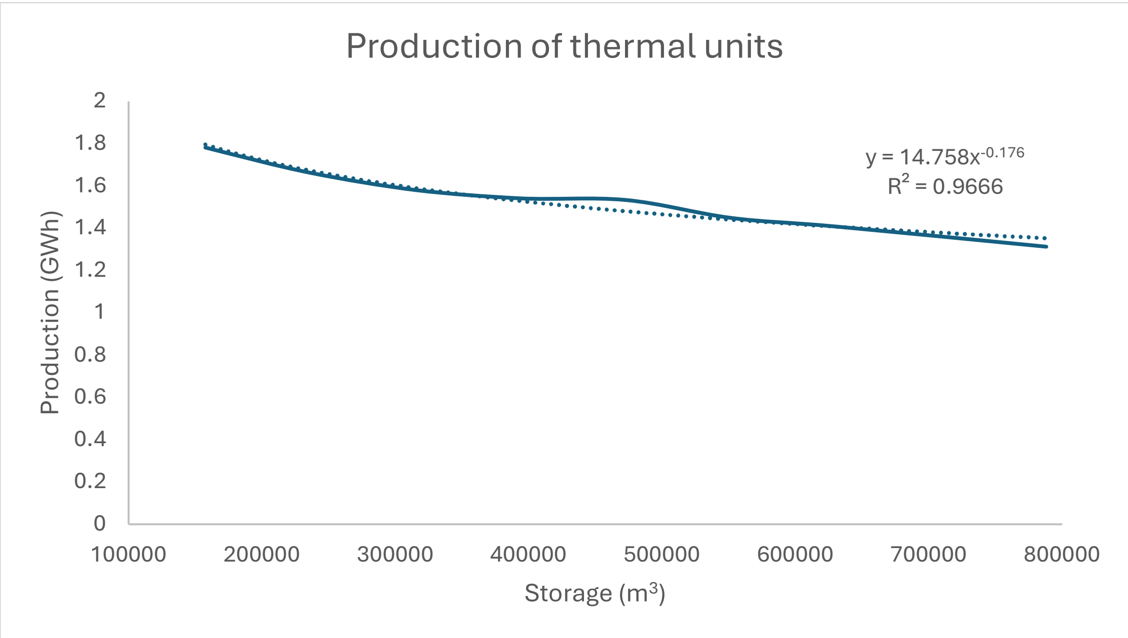
Εικόνα 2: Σύγκριση αποθεμάτων άνω ταμιευτήρα με και χωρίς θερμικές μονάδες.

Τέλος, στο πλαίσιο του σχεδιασμού του συστήματος, εξετάσαμε εναλλακτικά σενάρια, αλλάζοντας την χωρητικότητα του άνω ταμιευτήρα. Παρατηρούμε ότι:

- Όταν δεν υπάρχει θερμική μονάδα, αυξανομένης της χωρητικότητας, αυξάνεται και η αξιοπιστία καθώς και η παραγωγή ενέργειας από το σύστημα αντλησιοταμίευσης αλλά και η αποθήκευση ενέργειας.
- Όταν υπάρχει θερμική μονάδα, η αξιοπιστία μένει σταθερή στο 100%, αλλά η θερμική μονάδα παράγει όλο και λιγότερη ενέργεια, μειώνοντας σημαντικά το κόστος.



Εικόνα 3: Σχέση αξιοπιστίας – χωρητικότητας ταμιευτήρα.



Εικόνα 4: Σχέση παραγωγής από θερμικές μονάδες - χωρητικότητας ταμιευτήρα,

1. Introduction

1.1 Incentive

Renewable energy is becoming increasingly popular nowadays, following the trend towards decarbonisation. In this context, it is essential that the suitable computational tools are available to support decision-making, in the context of planning and management studies, thus making this transition as effective as possible. As the peculiarities of renewable energy, conventional power sources and energy storage elements introduce complexity, we need a generic and robust methodological framework to handle them. For this thesis we relied on water management tools, by attempting to adjust this knowledge to energy systems.

1.2 Research Objectives

This thesis delineates its primary research objectives as follows:

- Present the main components of a hybrid renewable energy systems and their operational rules;
- Analyse how each component contributes to energy production, taking into account meteorological data and technical features;
- Align the utilization of conventional units to an HRES with respect to their operational constraints;
- Solve the optimal energy flow allocation problem across renewable energy networks;
- Merge all the above into one executable software, herein called *Enerflow;*
- Apply the aforementioned into a real case study;
- Suggest other sustainable alternatives.

1.3 Thesis Outline

This thesis is divided into eight chapters.

The first chapter aims to introduce the reader to the main subject, incentive and outline of the thesis.

The second chapter gives a description of hybrid renewable energy systems and their components, but also an overview of their integration in Greece’s electricity mix.

Chapter three provides a brief bibliographic overview of optimal energy flow simulation throughout the years.

The fourth chapter sets the foundations of the simulation context and explains the methodological background of the transshipment problem.

The fifth chapter introduces the reader to the simulation framework under development, explaining analytically every step until problem’s solution.

In the sixth chapter, the user is introduced to *Enerflow* and gets familiar with its user interface.

In the seventh chapter, Enerflow is used for the under-scope case study of Sifnos island.

The eighth chapter includes simulation’s results with and without the thermal unit as a back-up, as well as experiments with different parameters.

The final chapter is a summary of the thesis’ conclusions and gives future perspectives of this research.

2. Overview of hybrid energy systems

2.1 Insight on renewable energy in Europe and Greece

The global energy landscape is currently undergoing a profound transformation as nations strive to combat climate change, reduce carbon emissions and enhance energy security. In 2022, Russia's invasion of Ukraine, highlighted the need to reduce Russian fuel imports, as a major consequence of the war was the energy crisis; energy and gas prices skyrocketed making electricity bills a nightmare for most Europeans.

The European Green Deal along with the policies such as the Renewable Energy Directives (RED II and RED III) and Greece's law 4951/2022 and 5037/2023 come as an answer, reflecting an urgent commitment to accelerate the deployment of renewable energy sources (RES). However, while solar, wind and other renewables offer sustainable and clean energy solutions, they also present challenges related to intermittency, grid stability and energy storage.

To bridge this gap, hybrid renewable energy systems (HRES) have emerged as a promising approach, combining multiple renewable sources with energy storage technologies to ensure reliability and efficiency. Yet, the effectiveness of these systems depends on precise coordination, making energy flows' simulation a crucial technological advancement. Without an effective simulation, even the most advanced hybrid systems risk inefficiencies, power imbalances and wasted energy potential.

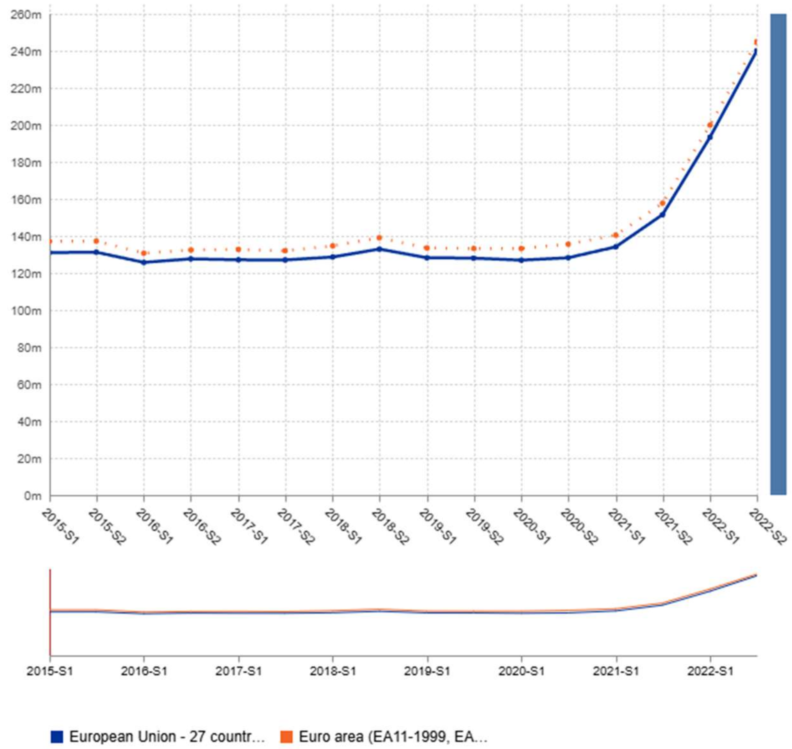


Figure 2.1 Electricity prices across European Union (Eurostat)

In in an attempt to alleviate the energy sector pressures induced by the armed conflict, the REPowerEU plan, launched in May 2022, aims to help EU to become energy independent. For a fact, EU gas imports coming from Russia were reduced from 45% to 15% over the years 2021 – 2023 and energy prices have been stabilised at a sufficient level. Since 2022, almost 96 GW of new solar energy was installed, the wind capacity increased by 33 GW, and 46% of electricity now comes from renewables (European Commission).

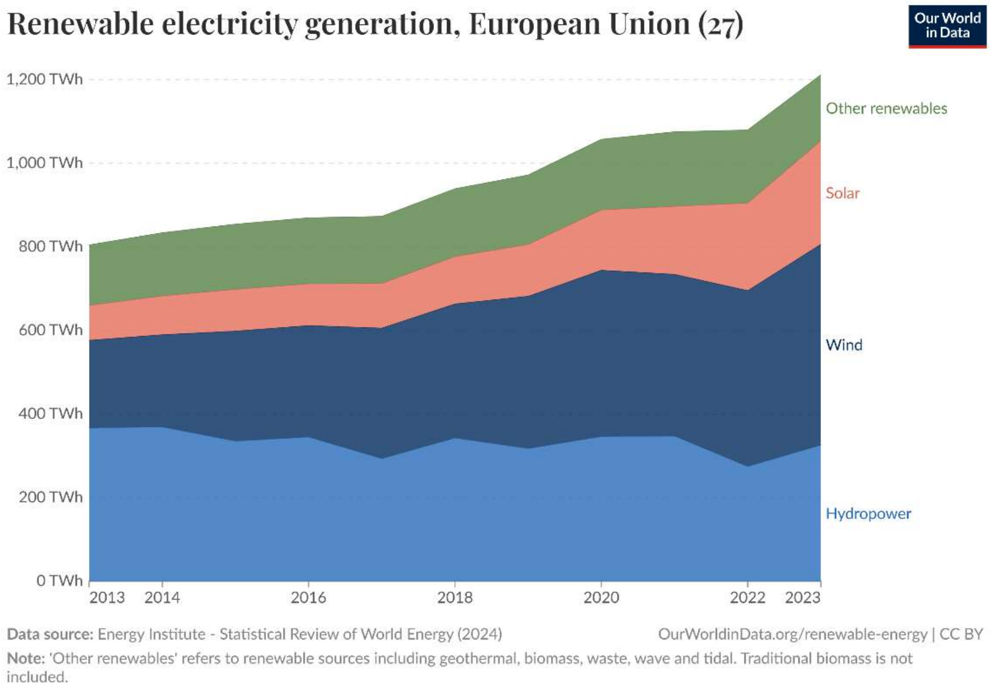


Figure 2.2 Renewable energy generation at European Union (Our World in Data)

For many years, Greece's primary source of electric power was lignite, whereas natural gas and oil played a significant role in the country's energy mix. However, in order to comply with EU's new laws and regulations, Greece managed to exploit its abundance of solar radiation and large wind power potential as well as the large number of hydroelectric plants.

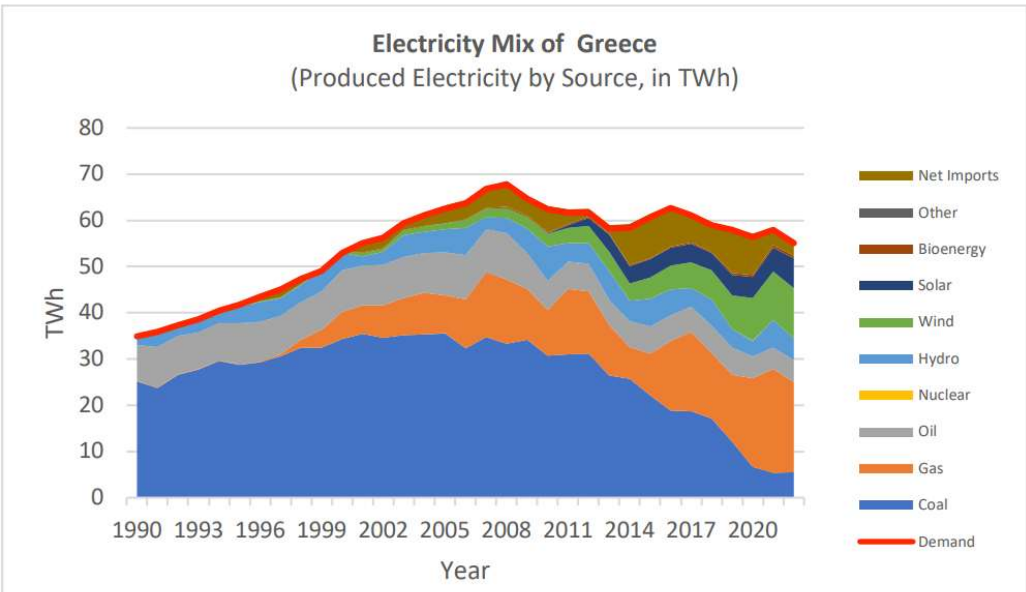


Figure 2.3 Electricity mix in Greece (Vlachogiannis, 2024)

More specifically, according to IPTO (Independent Power Transmission Operator) 2023 was a record year for renewable energy in Greece. The 57% of the energy mix consisted of solar, wind and hydroelectric power, which marks a 7% increase compared to the previous year's data. More specifically, solar energy reached 9.4 TWh which accounted to 19% of energy production, whereas wind energy reached 10.9 TWh (22% of production). Hydropower, at 3.9 TWh contributed 7.8% at the energy mix, while, on the other hand, lignite-powered production decreased by 73% in the last 5 years.

2.2 Hybrid energy systems

When the question of how the mankind will continue to live a comfortable life, benefiting from technological advances and ensuring secure and affordable electricity is posed, hybrid energy systems are the answer. While being extremely popular in the recent years, another step forward has been taken, by making their creation and operation part of regulations for a respected number of countries around the world.

A hybrid energy system can be considered as a mix of at least one renewable energy source, such as wind, solar, hydropower and a back-up generator (e.g., thermal units) to ensure energy autonomy in case of emergency. The following sections provide a brief overview of each possible component of an HRES.

2.2.1 Wind Turbines

Wind is the result of air movement from the higher to the lower pressure areas. Wind turbines utilize this wind speed transforming the kinetic power into mechanical. The power efficiency of a wind turbine depends on various wind power system components (such as turbine blades, shaft bearings and gear train, the generator and power electronics) and cannot exceed the Betz limit (59.3%). For a specific turbine, a nomograph called power curve is given by the manufacturer, which depicts the turbine's efficiency, and both cut-it and cut-out speeds. The usual wind speeds to be harnessed range between 2 m/s and 25 m/s.

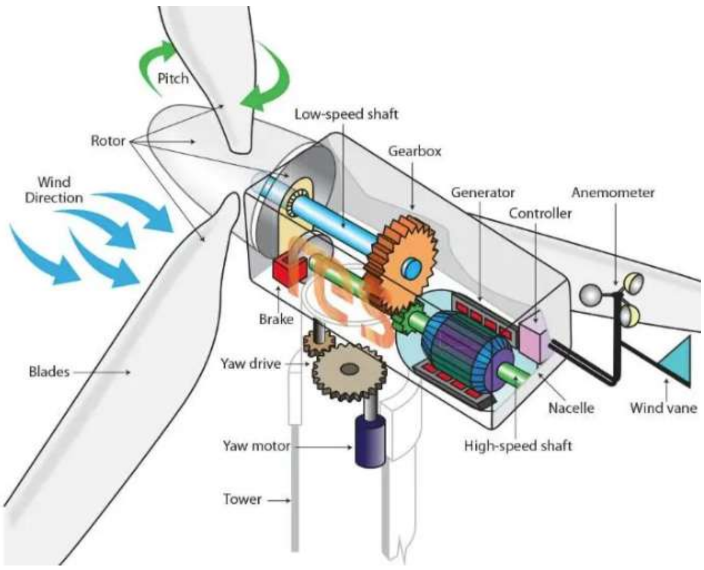


Figure 2.4 Wind turbine components (Energy Education)

2.2.2 Photovoltaics

The solar radiation received at the top of the Earth's atmosphere above a horizontal surface is called extraterrestrial (solar) radiation, R, and is expressed in W/m². Photovoltaic (or solar) panels exploit this radiation to produce electrical energy due to the photovoltaic effect, discovered in the year 1839 by Becquerel. Becquerel observed that while an electrode is exposed to light, its electric voltage increases. However, it took over a century until the operation of the first photovoltaic station in 1983. Solar panel efficiency continues to grow (with a remarkable increase of 15% from 1990) and depends on both the photovoltaic cell efficiency, and the total panel efficiency (panel size and color of protective backsheet, etc.)

Solar energy has undergone significant expansion in Greece, during the last years. In 2007, the total installed capacity was at 2 MW, this number escalated to 199 MW by 2010 and further proliferated, attaining 3,288 MW in 2020. By 2023, this number doubled reaching 6,369 MW. This expansion is highly reflected in Greece's electricity mix, with solar power constituting 12.4% of total electricity generation, e.g. 6.50 TWh.

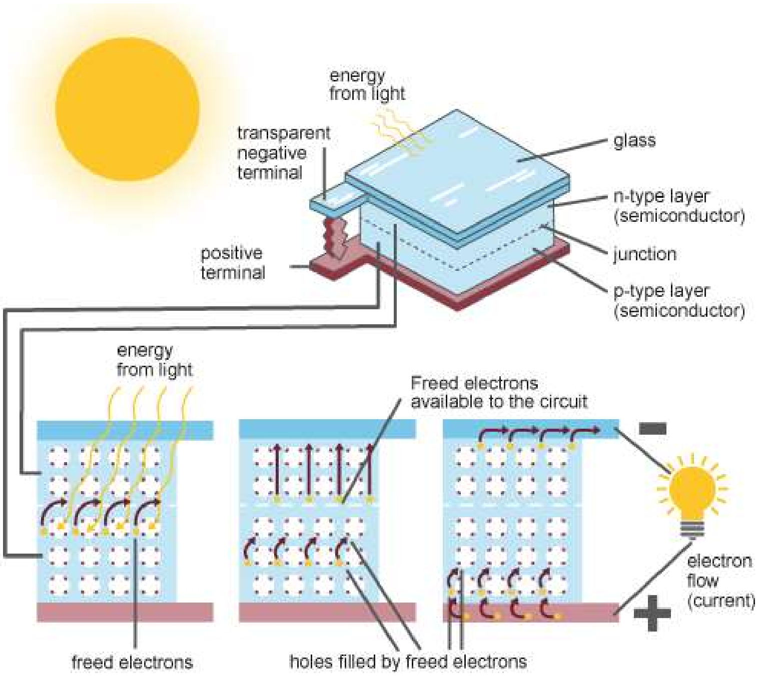


Figure 2.5 Inside a photovoltaic cell (U.S Energy Administration)

2.2.3 Small Hydropower Plants (SHPP)

To define a hydroelectric plant as small, the installed power capacity of the turbines must be under a certain limit, determined by national legislation, commonly between 10 to 30 MW. In Greece, the capacity cannot exceed the limit of 15 MW whereas this limit can vary considerably globally, for example in Canada, New Zealand and China the limit is 50 MW.

One can subdivide SHPPs into the following categories based on their utilization. First, the "storage facility" SHPPs which are mainly settled downstream of large dams to exploit the environmental flow.

Secondly, the most-used “run-off-river” plants that utilize the streamflow as it arrives and lastly, the “in-stream” plants that are rarely used and exploit the streamflow velocity to produce electric energy.

While in large hydropower plants, turbines usually operate under the nominal efficiency, that is not the case for SHPPs. With that in mind, hydroturbines’ selection is of utmost importance. Hydroturbines can be classified into two categories based on the criterion of how the water is guided to the turbine. First, the impulse turbines (e.g., Pelton wheels) take advantage of the kinetic energy that strikes the buckets to rotate. The second category, reaction turbines (e.g., Francis) operate under pressure and exploit both pressure and kinetic energy.

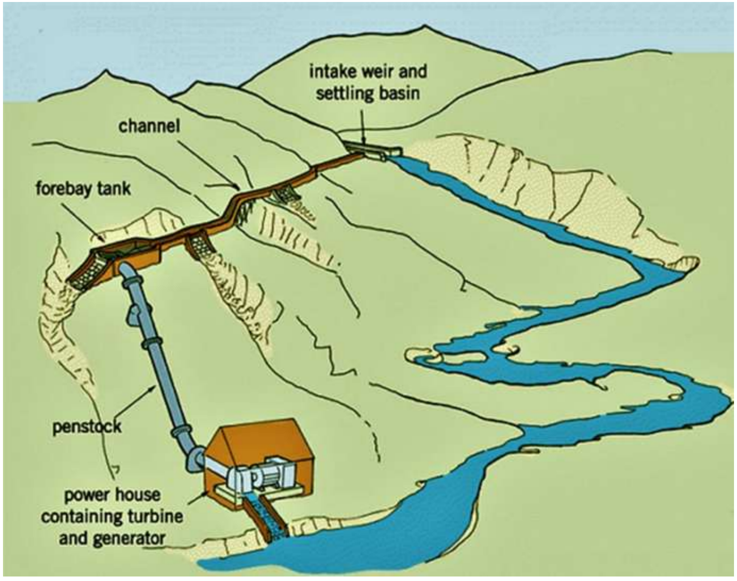


Figure 2.6 Typical layout of a run-off river plant (A. Efstratiadis, G.-K. Sakki & A. Zisos, Small hydropower plants)

2.2.4 Pumped Hydropower Storage (PHPS)

While large – scale storage of electricity in its raw form is unfeasible, its conversion to other forms of energy which can be stored and later reconverted to electricity is a common practice. The concept of electrical energy storage (EES) is more relevant today than ever, especially in the context of the energy crisis the world experiences. Typical instances of energy storage comprise battery energy storage systems (BESS), recognised as the most rapidly responsive dispatchable power source on electric grids, along with other power – to – gas technologies that transform surplus electricity into a more easily stored chemical form (with hydrogen one of the most popular ones). Currently, pumped hydropower storage (PHS, PHPS) is one of the most prevalent technologies in large – scale systems because of its high reliability and adaptability. The primary principles of EES consist of charging during low – demand periods and letting water flow through turbines to meet peak demand and they consist of multiple technologies with different characteristic in terms of efficiency, while a key problem related to time scale arises.

PHPSs can be classified into two main categories, the open loop systems that are connected to a natural water system, where the lower reservoir is connected to a river, and the closed loop systems that include both upper and lower reservoirs. The PHPS system can exploit excess electricity from other energy sources and reserve it for periods of increased demand. The main component is a pump hydro turbine or reversible pump turbine, operating as pumps during charging to transfer water from the lower to the higher reservoir, and as turbines when hydropower generation is required.

2.2.5 Conventional energy sources

Since renewable energy production is not only intermittent, but also inherits the uncertainties induced by natural processes (i.e., wind speed, solar radiation), it is necessary to integrate a conventional energy source to the hybrid system which will operate to meet the energy demand when necessary. Conventional energy is a form of non-renewable energy obtained from irreversible and depleting natural reservoirs that contain natural gas, fossil fuels, petroleum oil, coal or nuclear energy (Journal of Cleaner Production, 2021). Usual conventional sources include natural gas, coal and oil.

In Greece, lignite – fired power plants were the backbone of the country's electricity generation for decades. The need, however, to reduce carbon emissions forced the country to plan complete abandonment of lignite by 2028. Oil – fired power plants, play a significant role to ensure islands' electricity, as most of them are not yet connected to mainland's electricity grid.

2.3 Layout and operation

A typical layout of a hybrid energy system is presented in the figure below. Wind turbines and solar panels offer their produced energy to meet the demand goal. When this is not possible, water flows from the upper reservoir to the lower one, producing energy and if the demand is unmet, a back-up biogas generator covers the deficit. If on the other hand, there is energy abundancy, this surplus energy is used to pump water from the lower to upper reservoir.

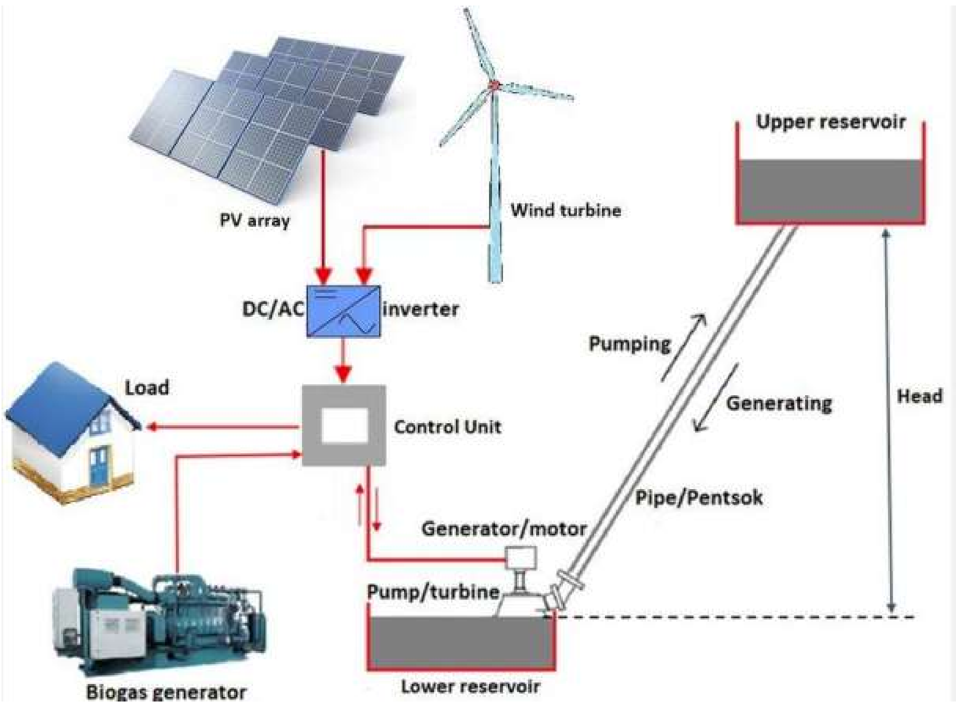


Figure 2.7 Typical layout of an HRES

2.4 Hybrid energy systems in Greece

The need of hybrid energy systems is largely pronounced in Greek islands, where residents often experience high fuel costs due to additional shipping expenses. According to Hellenic Organization of Tourism there are 227 inhabited islands in Greece. The Greek non-interconnected islands consist of 29 island systems, mainly located in the Aegean Sea (Zafeiratou & Spataru, 2019). Non-Interconnected Islands (NIIs) are the islands of the Greek territory whose Electricity Distribution Network is not connected to the Transmission System or the Distribution Network of the mainland.

Contrary to the rather increased fuel and oil costs for the Greek islands, their high wind and solar potential enables them to target energy independency based on renewable energy sources. The European Commission's initiative "30 renewable islands for 2030" includes 6 Greek islands (Astypalaia, Megisti, Ikaria, Psara, Lesvos, Tilos). These islands will receive assistance aiming to a carbon – free energy system.

2.4.1 Astypalaia HRES

Astypalaia is a Greek island of 1,376 residents located in the southeastern Aegean Sea. Its hybrid energy system is currently under construction and includes two phases. The first one consists of:

- Photovoltaics of 3.5 MW total nominal power
- Battery arrays of 10 MWh
- Oil station as backup

The first phase is to cover 60% of electricity demand, whereas the second one will reach 80% coverage.

2.4.2 Ikaria HRES

Ikaria is an island in the eastern Aegean with a population of 10,175 inhabitants (Hellenic Statistical Authority, 2021). Its hybrid energy system, "Naeras" is one of the two hybrid energy systems in Europe that combine hydraulic and wind energy. Its components are:

• A wind turbine park located on the hill "Stravokoudoura", including three wind turbines with 900 kW nominal power each.
• A small hydroelectric station with a turbine of 1.05 MW, exploiting the surplus water of the "Pezi" dam's reservoir, after ensuring that the water city's water supply needs and the environmental flow are met.
• A small hydroelectric station with two turbines of 3.1 MW total power, exploiting the surplus water of the pumped water storage.
• A pumped water storage consisting of two tanks of 80,000 m3 volume each located in "Proespera" and "Kato Proespera" respectively, and a 910,000 m3 volume reservoir in "Pezi".
• Pump station in "Kato Proespera" consisting of twelve-250 kW pumps.

2.4.3 Tilos HRES

Tilos is a small island with a population of 899 inhabitants (Hellenic Statistical Authority, 2021). Its hybrid energy system, which is a result of a Horizon 2020 project, started functioning in 2019 and consists of the following components:

- A wind turbine of 800 kW nominal power
- Photovoltaics of 160 kW nominal power
- Inverters of 20 kW nominal power
- Battery arrays of 2.8 MWh power

3. Literature review

3.1 Optimal energy flow

Since the early 1960s, the optimal energy flow problem (often referred to as optimal power flow problem – OPF) has been a fundamental component of power system optimization. It aims to identify the most effective way to generate power while both reducing operational losses or expenses and satisfying network constraints. Solving this problem, seems challenging due to the non-linear nature of the equations involved.

French researcher John Carpentier was the first to introduce OPF when he tried to frame the problem as a mathematical optimization one. His theoretical work attempted to consider of several constraints, such as voltage limits, power balance and generator capabilities. However, there are no practical applications due to the lack of sufficient computational tools during that period (Carpentier, 1985).

Based on Carpentier's work, H.W. Dommel and W.F. Tinney created an iterative progress by introducing Quadratic Programming techniques and consequently enhancing computational feasibility in 1968. Tinney, who previously innovated sparce matrix techniques for power flow analysis, played a crucial role in OPF solutions for real world systems (Dommel and Tinney, 1968).

In the 1970s, the research advanced thanks to O. Alsac and B. Stott, who introduced a numerical technique. More specifically, by using the Newton-Raphson method, they managed to enhance precision and convergence speed. Their work remains one of the most popular, even nowadays, as many modern solvers are based on it (Alsac and Stott, 1974).

Remarkable progress was made during 1980s and 1990s, with the integration of mathematical programming methods from the family of operations research, such as Linear Programming (LP), Quadratic Programming (QP) and Non - Linear Programming (NLP). While LP and QP reached great computing efficiency, they were based on many approximations, thus reducing precision. On the other hand, NLP was more accurate in depicting AC flow model, requiring, however, more processing power. Another significant advancement of these decades was the Interior Point Method (IPM), which solved the problem even in large scale systems.

With the start of the new century, metaheuristic and evolutionary algorithms surfaced as an alternative solution. Genetic Algorithms (GA), Particle Swarm Optimization (PSO), Ant Colony Optimization (ACO) and Differential Evolution (DE) gained popularity because of their ability to address more intricate problems regarding the free electricity market.

With the arrival of the Renewable Energy Sources (RES), came new issues mainly related to uncertainty and variability. This resulted in the emergence of stochastic methods that use probabilistic models to address fluctuations in renewable supply while ensuring system viability in worst case scenarios. These methodologies facilitated the efficient operation of power systems despite significant uncertainty, an essential criterion for contemporary energy grids.

In recent years, machine learning and artificial intelligence techniques are becoming a part of OPF problem solving. Deep learning models, reinforcement learning, and hybrid optimization techniques have been employed to forecast system behavior, enhance control strategies, and expedite OPF computations.

3.2 Simulation tools

As the popularity of hybrid renewable energy systems grows, simulation tools are of paramount importance, to both resemble the system and management decision making. A notable tool is HOMER (Hybrid Optimization Model for Multiple Energy Resources). The model was originally developed in 1993 as part of NREL Village Power Program. In 1997, it was rewritten in C++ to run on Windows PCs instead of Unix workstations running specialized optimization software. In 2000, a major upgrade was initiated to give the HOMER model the capability to model grid-connected systems. In 2004, that capability was expanded to include time-of-day and seasonal rates, avoided emissions, and improved handling of multiple generators. The user interface continues to improve with automated retrieval of resource data from the Web, simplified inputs, and HTML and XML export reports (The HOMER® Micropower Optimization Model). While using HOMER, the user inputs the cost and technical characteristics of the renewable source, daily and monthly load profile, also performing repeated optimizations, when required.

Figure 3.1 HOMER software (www.homerenergy.com)

Another well-known tool is Distributed Energy Resources Customer Adoption Model (DER-CAM). Designed in 2000 by researchers at Lawrence Berkeley National Laboratory, DER-CAM is a decision support framework with main goal to achieve optimal, cost-effective energy planning either concerning buildings or multi-energy grids. It solves the problem using mixed-integer linear program (MILP), unlike most models that use non-linear formulations. The key inputs consist of hourly load profiles, fuel costs, operating costs, the nature of the grid as well as the site's topology. When it comes to outputs, user gets the optimal selection and placement of distributed energy resources, total cost and carbon emissions.

Figure 3.2 DER - CAM software (www.https://gridintegration.lbl.gov)

4. Mathematical background

In this chapter, we provide a brief explanation of the methodological background, which sets the foundation for our simulation framework.

4.1 Basic concepts

4.1.1 Definition of a system

The system is defined as a set of independent elements characterized by (Mays & Tung, 1992):

- A boundary that determines whether the element belongs to the system or the environment.
- Interactions with the environment (inputs-impulses, outputs-responses).
- Relationships between the elements and the inputs and outputs.

A system can be static, if its loading conditions refer to a specific time or, generally, when its function does not have a time reference, or dynamic, when the loading conditions or even the characteristics of the system change over time.

4.1.2 Computational simulation process

Simulation is the generic technique of representing the operation of a dynamic system as it evolves in time (Winston, 1994). As a rule, simulation refers to discrete time steps rather than continuous time. A simulation model is a set of assumptions about the dynamic operation of the system, expressed through mathematical or logical relationships and usually encoded in a programming language.

4.1.3 The transshipment problem

The transshipment problem is an application of operations research, derived from graph theory (Smith, 1982). A graph is a mathematical entity, defined as a set consisting of ordered pairs of points. Any graph can be represented in the form (N, A), where N is a set of points called nodes, and A is a set of ordered pairs called arcs or edges. A digraph is a graph whose edges are oriented in direction, while a network is a graph whose elements (nodes and arcs) are assigned certain properties.

The topology of a graph consisting of n nodes and m edges is mathematically described by the $n \times m$ incidence matrix, with values $a_{ij} = 1$ if the direction is from node i to edge j, $a_{ij} = -1$ if the direction is inverse, and $a_{ij} = 0$, if there is no connection between node i and edge k.

In the transshipment problem, the following assumptions are made:

- total supply equals total demand
- at each node, the total incoming quantity equals the total outgoing minus the consumed (continuity equation)
- at each edge j, the quantity transferred x_j is positive and cannot exceed the conveyance capacity, u_j.

In case the first requirement is not satisfied, a virtual (dummy) node is considered, which absorbs the excess supply. In this way, the condition is:

$$\sum_{i=1}^{n} y_i = 0 \tag{4.1}$$

where y_i is the value of demand or supply at node i, with a positive or negative sign, respectively. The continuity equation is written in the form:

$$\begin{bmatrix} a_{11} & \cdots & a_{1m} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nm} \end{bmatrix} \begin{bmatrix} x_1 \\ \vdots \\ x_m \end{bmatrix} = \begin{bmatrix} y_1 \\ \vdots \\ y_n \end{bmatrix} \tag{4.2}$$

where a_{ij} is the element (i, j) of the incidence register, where i is the index of the node and j is the index of the interconnected edge. Finally, the capacity constraints are written in the form:

$$\begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix} \leq \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_m \end{bmatrix} \leq \begin{bmatrix} u_1 \\ u_2 \\ \vdots \\ u_m \end{bmatrix} \tag{4.3}$$

Assuming at each arc j a unit transport cost, c_j , the distribution of supply y_i over the m edges of the network, i.e. the calculation of the transported quantities x_j , is formulated as a linear programming problem (more precisely, *network linear programming*, NLP) with a cost function:

$$f(x_1, \dots, x_m) = \sum_{j=1}^{m} c_j x_j \tag{4.4}$$

The matrix formulation of the NLP problem is:

$$\begin{aligned} & minimise\ f(\boldsymbol{x}) = \boldsymbol{c}^T \boldsymbol{x} \\ & s.t. \boldsymbol{A}\,\boldsymbol{x} = \boldsymbol{y} \\ & \boldsymbol{0} \leq \boldsymbol{x} \leq \boldsymbol{u} \end{aligned} \tag{4.5}$$

where $\boldsymbol{x}$ is the control variables' vector (e.g. the quantities to be transferred), $\boldsymbol{c}$ is the cost price vector, $\boldsymbol{A}$ is the incidence register, y is the supply and demand vector, **0** the zero vector and lastly, $\boldsymbol{u}$ is the capacity vector.

We remark that since the incidence matrix $\boldsymbol{A}$ has a very simple, and at the same time sparse, structure (its elements are -1, 1 and 0), the NLP problem may be solved through specific algorithms, i.e. the *network simplex* method, that are significantly faster than conventional approaches, namely the well-known simplex method for generic linear optimization problems.

4.2 Using NLP within water resource systems analysis

The network structure of water resource systems enables the development of models based on the network linear programming context. As explained, NLP has a particular mathematical formulation, which can provide much faster solutions than general linear programming models do.

Models based on NLP have been used in a variety of water resources planning and management applications. For example, Kuczera (1989) introduced a multiperiod optimization scheme, where the boundary conditions between adjacent periods are taken into account through the use of virtual carryover arcs. However, the variety of network LP schemes (e.g., Graham et al., 1986; Labadie, 1995; Fredericks et al., 1998; Dai and Labadie, 2001) are essentially simulation models, performing static optimisation for a single time period to find the least cost flow allocation through network-type water systems. The optimization is based either on real economic criteria or on artificial costs, which are assigned to preserve water rights and water use priorities.

NLP is also implemented within the decision support system "Hydronomeas", as an elegant method for handling the step-by-step simulation procedure as a transhipment problem. The methodological framework of Hydronomeas follows the parameterization-simulation-optimization approach, comprising stochastic simulation, network linear optimization for the representation of water fluxes, and multicriteria global optimization, ensuring best-compromise decision-making. Its generic context is set by Koutsoyiannis et al. (2003), while Efstratiadis et al. (2004) focus to the formulation of the NLP problem, and its application to the raw water supply system of the city of Athens. Details are provided in the documentation report of the software (Efstratiadis et al., 2007). A characteristic screenshot of Hydronomeas' interface illustrating the Alfeios hydrosystem is shown in Figure 4.1.

The key elements of the NLP methodology within Hydronomeas are transferred to the optimal energy flow allocation problem, after essential adaptations and improvements. Chapter 5 explains the conceptual framework and the associate computational procedure, while Chapter 6 introduces the *Enerflow* tool, which implements the NLP equivalent in hybrid renewable energy systems.

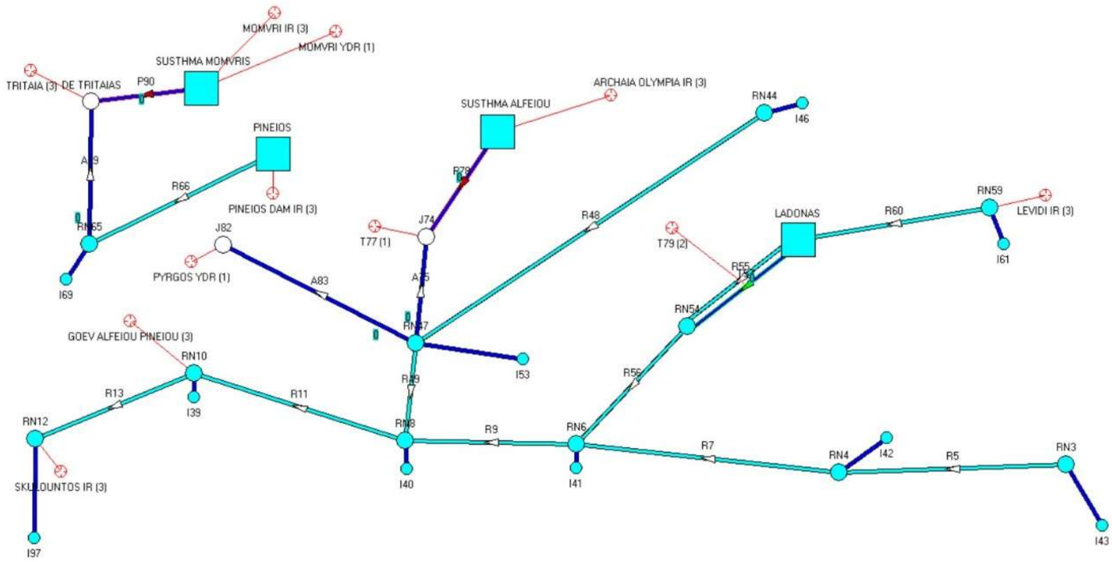


Figure 4.1 Example of network type schematization of Alfeios hydrosystem within Hydronomeas (Kolioukou et al., 2024)

5. Simulation framework for energy flow allocation

In this research, we attempt to give a solution to energy flow allocation problems, inspired by the theoretical background of Hydronomeas, namely the use of NLP within simulations. As explained in Chapter 4, the aforementioned method is often used to water management problems, in this case we adjust it and its parameters to be applicable for hybrid renewable energy systems.

5.1 Generic context

5.1.1 Problem statement

As inputs of the simulation model, we consider the energy supply as well as the energy demand, the way supplies and demands are linked, the financial costs of the routes and the priority order that one must adhere to. The simulation is executed in finite time steps (hourly).

Due to the presence of numerous degrees of freedom, knowing the desired outputs of the reservoirs and turbines alone is insufficient to determine all the decision variables within the system, such as the actual outputs and their distribution across the network (flows). This situation arises when at least one of the following conditions is met:

- the transfer of outflows from sources to consumption is not straightforward, as there are alternative routes available, often with varying costs;
- there are multiple conflicting objectives that need to be fulfilled simultaneously;
- the total demand exceeds the total available water supply.

With the above taken into consideration, we determine that we must deal with linear programming problems which can be formulated in a specific form called transshipment problem.

5.1.2 The virtual digraph system

Let us consider a simple energy supply - demand system. The aim is to represent the decision variables of the mathematical model of the system by means of an ideal digraph, so that they all correspond to the control variables of a transshipment problem. Since the digraph preserves the topology of the real system, a formulation of the problem is sought that guarantees the satisfaction of the basic requirements, ensuring the optimal distribution of available resources to the individual components. This is done by defining appropriate supply and demand values at the nodes, and appropriate capacity and unit cost values at edges. The cost must be positive, i.e., it must reflect a penalty, and negative when a supply is imposed to satisfy a demand.

A virtual cumulative (*dummy*) node is introduced into the model, where the energy that is either consumed or rejected at the nodes is conveyed. This node is set so that the constraints of the transshipment problem are valid, particularly the global continuity equation (i.e. total supply equal to total demand).

5.1.3 Calculation of unit costs model

The way in which unit cost values are determined constitutes an extremely important and original aspect of the mathematical framework developed, as it ensures that the three requirements set out in 4.1.3 are met. According to these, the allocation of water resources in the water system must ensure, in the following order of priority:

1. strict adherence to natural constraints.
2. hierarchical satisfaction of objectives and operational constraints.
3. minimizing the cost of transporting outputs from sources to consumption sites.

For this reason, the variables of the model, as assigned to the network edges, are grouped into four levels of importance, so that the unit cost (in absolute value) of each branch belonging to level k exceeds the cumulative cost of the branches of all previous categories, i.e.:

$$|c|^{[k]} = \sum_{j=1}^{n(k)} |c_j| + \varepsilon \tag{4.1}$$

where c_j the unit cost of edge j, $n(k)$ is the number of edges ranked up to the k level of significance, and ε is a small, positive value. A direct consequence of 4.1 is both the independent minimization of the total cost of each class and the priority minimization of cost values belonging to higher classes.

5.1.4 Defining the capacity vector

The elements of vector **u**, i.e. the conveyance capacities of the edges, correspond to either real or virtual quantities. The former refers to physical constraints of the network. The others express desired quantities, such as the current node demand.

5.1.5 Time steps result

After solving the problem, the optimized variables $\boldsymbol{x}$, i.e. the flows of the digraph's edge, are assigned to the variables of the real components of the system. With the simulated time step variables known, it is examined whether the objectives and constraints of the system are satisfied. If the desired value of a goal is not achieved, then a failure is recorded in the current time step.

5.2 Estimating the energy production of each component

Before forming the energy flow allocation problem, it is crucial to estimate the energy production by all HRES components, which will be next the supply flow input. We remark that while the simulation problem handles inflows as known quantities, in real-world cases, the actual energy production of each component cannot be perfectly known a priori (only predicted). Nevertheless, this is a common assumption of all kinds of simulation approaches across a wide range of systems analysis problems.

The procedure for each component type is described below.

5.2.1 Solar power

The efficiency of a solar panel is determined by the photovoltaic cell efficiency, depending on the cell design and silicon type and the total panel efficiency, based on the cell layout, configuration, panel size etc. The latter is measured under Standard Test Conditions (STC), based on a cell temperature of 25°C, solar irradiance of 1000 W/m^2 and air mass of 1.5, for 2.74 hours. Exposure of the photovoltaic cells to temperatures that exceed the STC one results in a decrease in efficiency and is described by applying a power temperature coefficient (%/°C).

The hourly power production is calculated according to the following formula:

$$P_{hourly} = N \frac{n_{act}}{n_{nom}} min[n_{nom}\ R\ A_{panel}, P_{nom}] \tag{5.2}$$

where N is the number of solar panels, n_{act} is the adjusted PV efficiency against temperature effects, n_{nom} is the nominal efficiency, R (W/m^2) is the solar radiation and T (° C) is the ambient temperature, A_{panel} is the PV area, and P_{nom} is the nominal power, which is achieved under the STCs.

The adjusted PV efficiency against temperature effects is being calculated by the following formula:

$$n_{actual} = n_{nom} - a_T * max(T - 25, 0) \tag{5.3}$$

where a_T is the power temperature coefficient.
The relationship between solar radiation and power output is typically considered linear and is described in the following figure. For solar radiation values exceeding 1000 W/ m^2, the module produces its nominal power.
With the above being said the user has to input the following data:

- Hourly solar radiation (W/ m^2) time series
- Hourly Temperature time series
- Nominal P provided by the manufacturer
- Nominal efficiency
- The power temperature coefficient, a_T
- The area of the panel, A_{panel}
- The number of panels, N

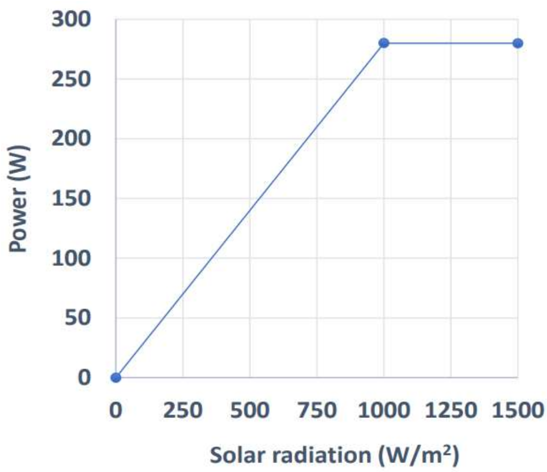


Figure 5.1 A typical power – solar radiation curve of PV panels (Efstratiadis et al., 2024)

5.2.2 Wind power

To calculate the wind power produced one needs the power curve of the wind turbine as well as the wind speed time series.

However, the wind speed has to be modified due to the height difference between the anemometer, where it is typically measured, and the wind turbine hub. To estimate the mean wind speed u_2 at a height z_2, based on a known value u_1 at a height z_1, the formula used is:

$$\frac{u_2}{u_1} = \frac{ln\left(\frac{z_2}{z_0}\right)}{ln\left(\frac{z_1}{z_0}\right)} \qquad 5.4$$

where z_0 is the roughness length, a corrective measure to account for friction effects to wind flow due to terrain obstacles.

The power curve is a nomograph, revealing the relationship between wind speed (m/s) and the electrical power (kW), providing useful information about the cut–in and cut–out speeds, and the nominal power. A typical power curve is presented in the figure below:

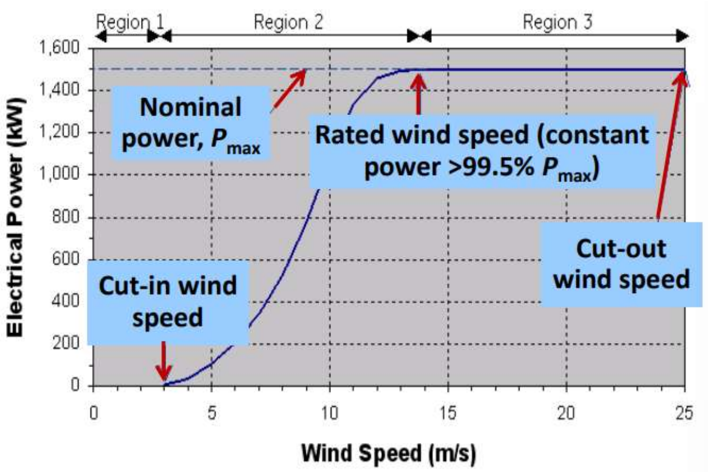


Figure 5.2 A typical power curve of wind turbines (Efstratiadis et al., 2024).

The user has to input the following data:

- Turbine’s power curve (provided by the manufacturer)
- Wind speed (m/s) time series
- Turbine's tower height (m)
- Anemometer elevation from ground level (m)
- Surface roughness parameter

5.2.3 Small Hydropower Plants

To estimate the energy produced from a small hydropower plant we need its characteristics and the inflows. Assuming two turbines of power capacity, P_1 and P_2 of specific type, the input data should consist of:

- Streamflow time series at the intake, q, after subtracting environmental flows.
- Gross head, H_G
- Total efficiency, $\eta({}^{q}/{}_{q_{max}})$, expressed as function of rated discharge
- Minimum discharge for energy production $q_{i,min}$ (typically, 10 – 30% of $q_{i,max}$)

The maximum (nominal) discharge of each turbine is given by:

$$q_{i,max} = \frac{P_i}{\gamma\, \eta_{i,max}\, h_n} \qquad 5.5$$

where $\eta_{i,max}$ is the total efficiency at the maximum discharge, which depends on the turbine type, γ is the specific weight of water (9.81 kN/m^3) and h_n is the net head, i.e. the gross head reduced by the hydraulic losses h_L.

Hydraulic losses include friction ones across the penstock, as well as local losses. For given discharge, Q and pipe diameter D, we calculate flow velocity as follows:

$$V = \frac{4Q}{\pi D^2} \qquad 5.6$$

By using the Darcy – Weisbach formula, we get the energy gradient J across the pipe:

$$J = f\frac{1}{D}\frac{V^2}{2g} \qquad 5.7$$

where f is a friction factor estimated by the Colebrook – White equation:

$$\frac{1}{\sqrt{f}} = -2\,log\left(\frac{\varepsilon}{3.7D} + \frac{2.51}{Re\sqrt{f}}\right) \qquad 5.8$$

where $Re = \frac{VD}{v}$ is the Reynolds number and ε/D is the relative roughness, ε is the absolute roughness of the specific pipe and v is the kinematic viscosity of water, function of temperature. For example, for T = 25 °C, v = 1.1*10^{-6} m^2/s.

To estimate f we follow an iterative procedure, by defining an initial estimate for f and redefining it until convergence is achieved.

The friction losses, are given by:

$$h_f = fL\frac{8Q^2}{\pi g D^5} \qquad 5.9$$

The minimum discharge of each turbine is expressed as ration of the maximum one:

$$q_{i,min} = \theta_i q_{i,max} \qquad 5.10$$

The flow passing through the first turbine is given by:

$$q_{T1} = min(q, q_{1,max}) \tag{5.11}$$

If $q > q_{1,max}$ then the surplus flow passing through the second turbine is:

$$q_{T2} = min(q - q_{T1}, q_{2,max}) \tag{5.12}$$

The hydraulic losses and thus the net head, h_n, are estimated as a function of the total discharge $q_{T1} + q_{T2}$, which is diverted to the turbines.
For $q_{Ti} < q_{i,min}$, the turbine is set out of operation while when $q_{Ti} > q_{i,min}$ the energy produced by each turbine is:

$$E_i = \eta(q_{T1})\, \gamma\, q_{T1}\, h_n\, \Delta t \tag{5.13}$$

Thus, the volume exploited by each turbine is given by:

$$V_i = \begin{cases} 0, & Q_{Ti} < Q_{i,min} \\ Q_{Ti}\Delta t, & Q_{Ti} \geq Q_{i,min} \end{cases} \tag{5.14}$$

The analytical formula for turbine efficiency n_T as function of rated discharge, q/q_{max}, is given by:

$$n_T = n_{min} + \left(1 - \left(1 - \left(\frac{\frac{q}{q_{max}} - \theta}{1 - \theta}\right)^{\alpha}\right)^{b}\right)(n_{max} - n_{min}) \tag{5.15}$$

Where n_{max}, n_{min} are the upper and lower efficiency values within the feasible flow range, $\theta = q_{min}/q_{max}$, and a, b are shape parameters.

The most used turbine types that are applied in SHPPs are Pelton and Francis and their parameters are given in Table 5.1.

Table 5.1 Characteristic properties of Pelton and Francis turbine types

	Pelton	**Francis**
θ	0.10	0.15
n_{min}	0.78	0.33
n_{max}	0.89	0.93
a	1.0	0.78
b	8.0	3.11

Even though the streamflow data is often given on daily scale, the optimal energy flow should be calculated on an hourly step, given the fact that energy demand changes dramatically throughout the day. To adapt the daily data to hourly we assume that each hour the streamflow is:

$$q_{hourly} = \frac{q_{daily}}{24} \tag{5.16}$$

It is deduced that; the order in which the turbines will operate plays a pivotal role to the total energy produced. For this reason, the software executes an optimization to choose which turbine should be the first to achieve greatest performance rates.

5.2.4 Pumped Hydropower Storage Systems

PHPS systems are able to both produce and store energy in means of water, depending on whether there are energy deficits or surpluses, thus the storage's time series is dependent on the other production components and is a result of a simulation.

The conventional PHPS system consists of two reservoirs, the capacities and geometries of which are user's inputs. Moreover, the height of the intakes, the efficiencies of the turbine and pump, the percentage of hydraulic losses, are necessary to estimate the energy produced, or stored, in terms of water being pumped to the upper reservoir.

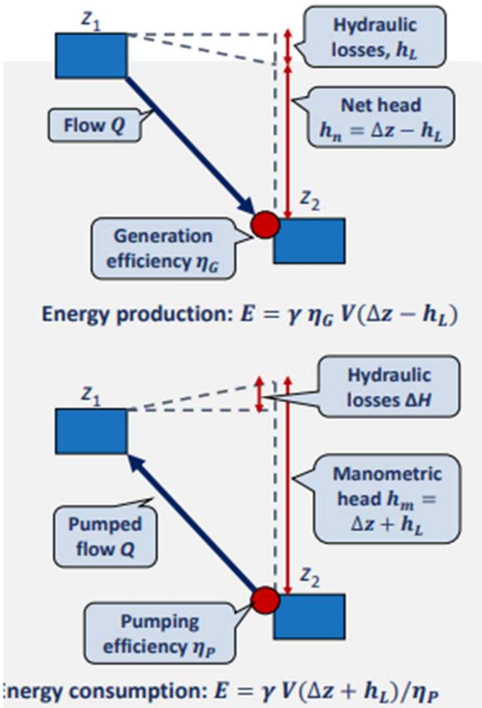


Figure 5.3 PHS system's energy consumption and production (Efstratiadis et al., 2024)

In this respect, we calculate the energy produced or stored given the water volumes flowing through the turbines or pumps, respectively, as given below:

$$E_{prod} = \gamma\, \eta_G V_{prod}(\Delta z - h_L) \tag{5.17}$$

where η_G the turbine's efficiency, V_{prod} the water volume flowing through the turbines, and $h_n = \Delta z - h_L$, the net head.

$$E_{cons} = \gamma \frac{V_{pump}(\Delta z + h_L)}{\eta_P} \tag{5.18}$$

where η_P the turbine's efficiency, V_{pump} the water volume pumped, and $h_n = \Delta\mathrm{z} + \mathrm{h_L}$, the manometric head.

5.2.5 Conventional units

This software allows users to add a conventional source of electricity, to ensure every demand is met when required. As mentioned before, the integration of conventional units to our system, raises several challenges related to its operation. The user has to determine the profile of the conventional unit included in the system.

5.3 Configuration of energy flow allocation as transshipment problem

As previously mentioned, solving the transshipment problem requires the definition of vectors c and u, both of which deriving from user inputs.

In the case of a demand node, the user must specify the priority in which the demand must be satisfied, while when they add an energy source to the simulation model, they should also specify its actual hourly cost. The virtual costs depend on real costs and priorities and are calculated in the virtual system phase.

5.4 The virtual system

While the user creates a visual, true system consisting of RES, demand nodes and interconnectivity, *Enerflow* creates a virtual system to solve the transshipment problem mentioned in chapter 4.1.3. Subsequently, user inputs are used to create the problem's vectors $\boldsymbol{A}, \boldsymbol{u}, \boldsymbol{y}, \boldsymbol{c}.$ The problem's nature changes rapidly when a PHS system is integrated into the system because the energy produced or stored directly affects the optimal allocation of energy flows.

First, a *dummy* node is imported to the virtual system as outlined in section **Error! Reference source not found.**. Once supply and demand nodes are connected to the *dummy* node, topology matrix $\boldsymbol{A}$, is created. *Dummy* node is essential, because it collects all the supplies and demands, maintaining the balance and ensuring the inflows are equal to outflows.

In the figure below, one can see the true elements of a network and their connections, once dummy node is added.

It is deduced that edges that link supply nodes and demand nodes with dummy are not the same and cannot carry the same quantities, but this is explained analytically when defining the vectors.

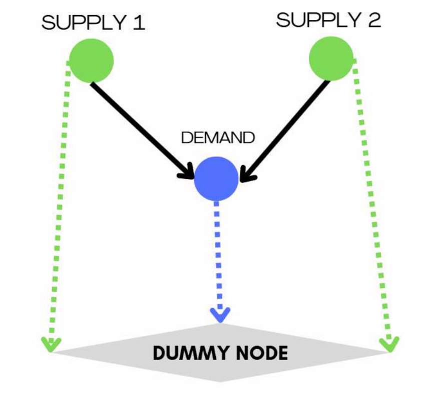


Figure 5.4 Example of a virtual network

5.4.1 Creating virtual system's vectors

After the virtual graph and the topology matrix are created, we continue by defining the vectors essential for the solution of the problem as referred to in chapter 4. Vector $\boldsymbol{y}$ is created first and depends on supply and demand values. The procedure is as follows:

- For each supply, the correspondent value is assigned to $\boldsymbol{y}$
- For each demand, 0 is assigned to $\boldsymbol{y}$
- To *dummy* node, the negative sum of the previous values is assigned to $\boldsymbol{y}$

Vector $\boldsymbol{u}$ pertains to edges rather than the nodes and signifies their capacity. Most specifically, given supply and demand values for each step, we create $\boldsymbol{u}$ after we divide edges to either true or virtual. True edges are created by the user and represent physical connection between suppliers and demands. Consequently, their capacity is defined by physical constraints of the system.

Virtual edges are those connecting supplies and demands to *dummy* node and their capacity is the supply and demand values respectively.

Finally, $\boldsymbol{c}$ represents costs and for true edges is the real cost input by user, and for virtual edges connecting supplies to *dummy* is 0 , whereas for those connecting demands to *dummy* given by:

$$c_j = \frac{-1}{priority_i} \tag{5.19}$$

where c_j the cost of virtual link j connecting the demand node i to the *dummy* one and $priority_i$ is the priority set by the user, according which the demand has to be satisfied.

As long as all the variables needed are created, we use a linear solver and find the optimal $\boldsymbol{x}$, so as to minimize the cost as described in equation 4.5.

5.4.2 Hybrid energy system with PHS system

As mentioned previously, the ability to store water (and consequently energy) alters significantly the nature of the problem since producing energy can cover the deficits, whereas, on the other hand, pumping water, i.e. storing energy, can cover potential future deficits.

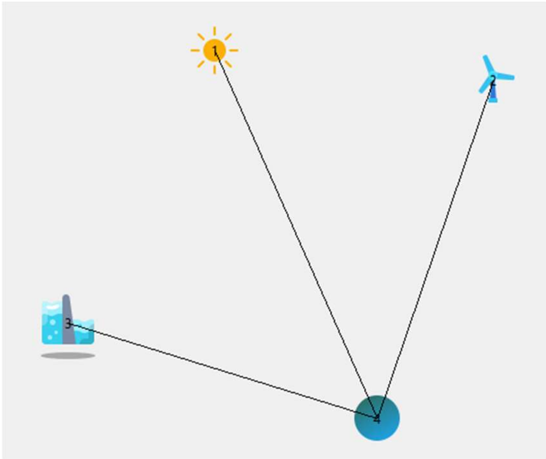


Figure 5.5 User created hybrid energy system with PHS

For this reason, the problem variables are dependent on previous energy flows given that water storage changes.

Until this case, the virtual depiction of an energy component coincided with the real one. However, we choose to interpret the two reservoirs of the PHS system as one node. To determine energy flows we only need the upper and lower storages, whereas water flowing through the turbines producing energy and water pumped is an internal process and its detailed estimation is of no need for the specific problem.

A notable modification involves introducing an additional virtual node into the system, referred to as *surplus* node. This node is designed to accumulate the excess energy generated by the supply nodes, in order to be utilized by pumping water, if technically feasible. To achieve this, all supplies are connected to *surplus* node, while the latter is linked to both the PHS system and the *dummy* node, as shown in Figure 5.6.

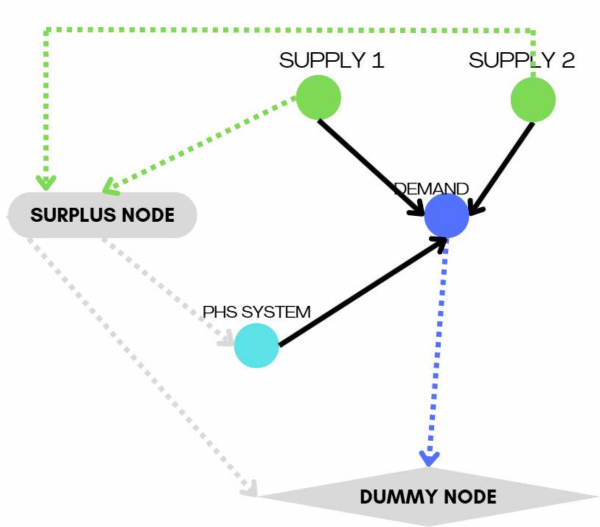


Figure 5.6 Virtual system including surplus and dummy nodes

Table 5.2 Vector y

Node i	y_i
Supply	Supply value
Demand	0
PHS system	Potential energy produced
Surplus	0
Dummy	$\sum_{i=0}^{n-1} y_i$

To accommodate the new virtual system's needs, all the variable vectors require updating. First, vector $\boldsymbol{y}$, that corresponds to supply and demand needs to each node, alters as shown in Table 5.2.

We notice that supply, demand and *dummy* nodes maintain the value mentioned in section 5.4.1, whereas PHS system node is assigned its potential energy supply as referred to in equation 5.17.

Creating the capacity vector $\boldsymbol{u}$, we establish the fundamental rules for the operation of the PHS system. Once again, we divide the edges in categories based on the nodes they connect. True edges still represent the true connections input by the user. However, if the edge connects the PHS system to demand node, the correspondent $\boldsymbol{u}$ value is given by:

$$u_i = min\ (potential\ energy\ produced, demand) \qquad 5.20$$

Nevertheless, if the edges are virtual (i.e., connecting true nodes with virtual ones) the following cases are identified. To begin with, virtual nodes that connect supplies to *surplus* are limited to transferring at most their respective supply values at each time step. If, on the other hand, the edge connects *surplus* node to PHS system node u value is given by:

$$u_i = max\ ((min\left(\sum supply\,, potential\ energy\ consumed\right), 0) \qquad 5.21$$

It is important to highlight that both the energy production and energy consumption values that are mentioned in equations 5.20, 5.21 are the potential ones, i.e. the energy that the two reservoirs can produce or consume based on their water storages and are estimated as given in equations 5.17 and 5.18. For the edge connecting PHS system to *dummy*, the transferred value is:

$$u_i = potential\ energy\ prod + min\left(\sum supply\,, potential\ energy\ consumed\right) > 0 \qquad 5.22$$

As shown in Table 5.3, vector $\boldsymbol{c}$, is formatted in way that respects the level rules explained in section 5.1.3. More specifically, our virtual system should force energy flows from *surplus* to PHS system node and not *dummy.*

*Table 5.3 Vector **u***

Edge i	u_i
True link	Demand value
PHS system to demand	min(potential energy produced, demand)
Supplies to *surplus*	Supply value
Surplus to PHS system	max((min(supplies, potential energy consumed),0)
PHS system to *dummy*	max((potential energy produced + min(supplies, potential energy consumed, 0)
Supply to *dummy*	Supply value
Demand to *dummy*	Demand value
Surplus to *dummy*	$\sum supplies$

5.4.3 Introducing thermal units to a hybrid system

The introduction of conventional thermal units enacts significant transformations, as their way of operating is much more complicated.

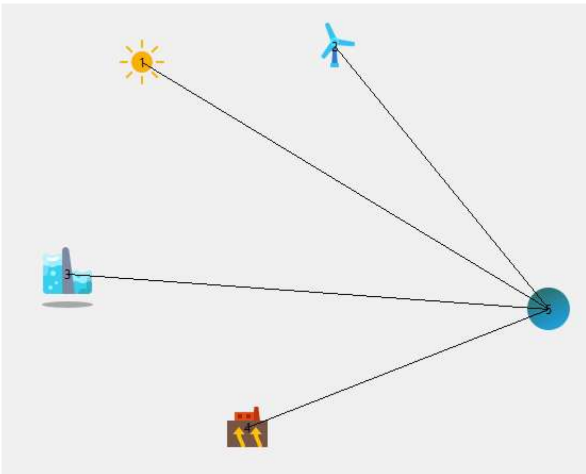


Figure 5.7 Hybrid energy system including thermal station

Activating a thermal unit necessitates more than one time step (in this case, hour), thus implying to follow an iterative procedure. Its usage is based on many administrative rules (such as keeping it open incessantly) which are established by each country's legislation.

For thermal units we assume that no such administrative rule exists and activate the unit when needed, considering the maintenance of mandatory functional regulations. Given the thermal unit's operation profile, we can easily estimate the lag and close times, the minimum open time and the minimum close time.

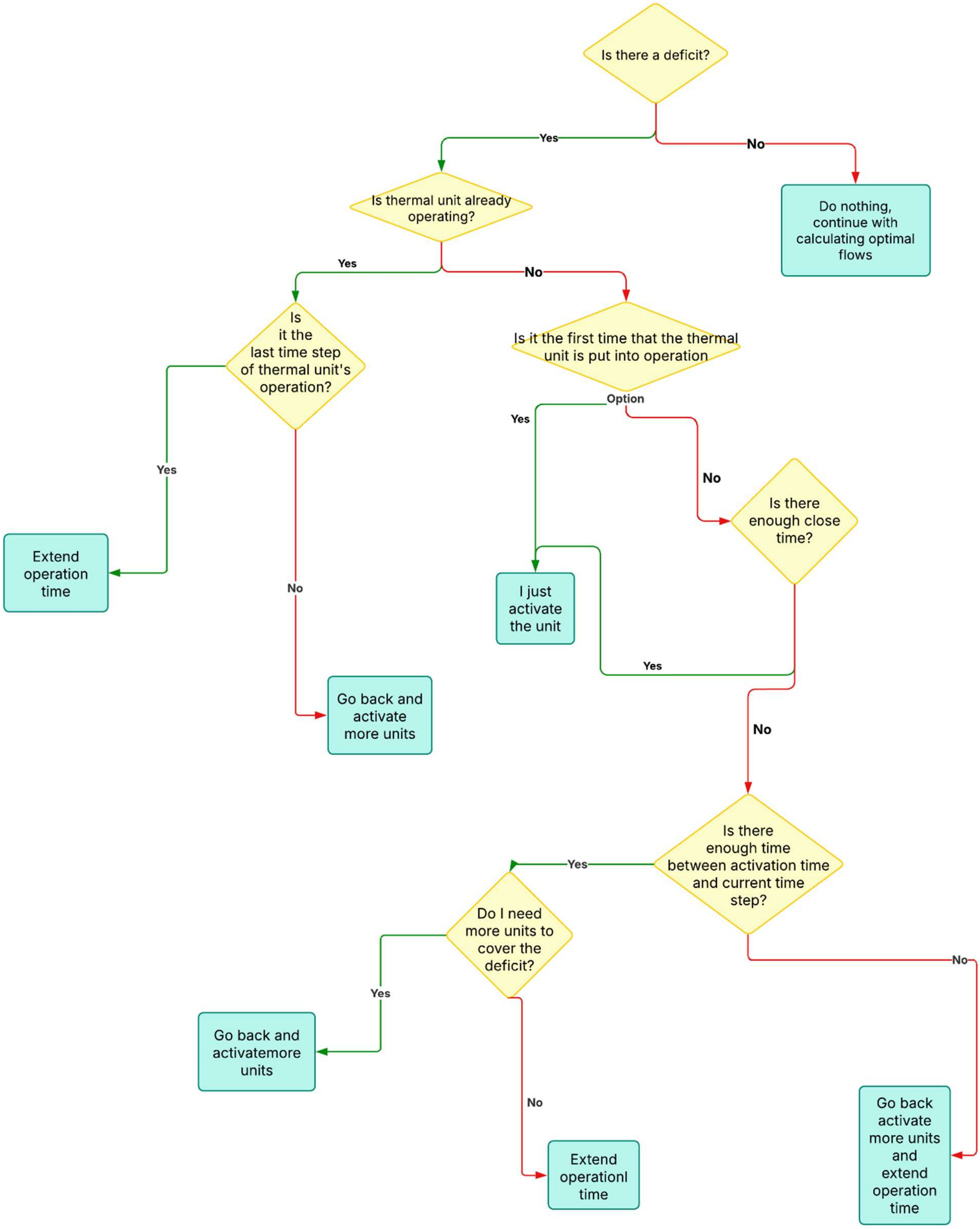


Figure 5.8 Flow Chart of thermal unit operation decisions

More particularly, if there is a thermal unit to our system and the energy demand is still not fulfilled, we proceed to activate as many thermal units as we need:

$$N = min\left(\frac{deficit}{max\ energy\ production}, N_{total}\right) \tag{5.22}$$

where N is the number of units needed for the specific deficit, N_{total} is the number of units available and $\max energy\ production$ is the maximum energy a single unit can produce.

After calculating the required number of units to use, we continue to the activation following the flow diagram of Figure 5.8.

By following the steps explained above, we ensure that:

- There is sufficient close time and if there is not, we keep the thermal unit operational
- If we need more units activated while already operating on lower power, we return to activate the maximum units needed from the start

The whole method follows an iterative process, going steps back to both respect thermal constraints and meet the energy demands and by changing the vector $\boldsymbol{u}$, by assigning new supply values to thermal unit, instead of default zero.

Subsequently, the process remains as before, by formatting the costs in a way that activating thermal units will be the last action, after trying to cover the demands from the RES supplies, or the PHS system.

6. Development of *Enerflow*

Enerflow is a software aiming to provide the user with an easy, user - friendly environment able to both simulate hybrid energy systems and calculate the optimal energy flows to achieve the minimum cost with respect to other parameters (such as the prioritization of demand nodes), based on solving the abovementioned transshipment problem. It was developed in Python and is an executable app, thus being compatible with various systems.

6.1 Enerflow’s user interface

To make *Enerflow* an easy, user-friendly software, we developed an understandable and simple graphic user interface (GUI). The starting screen appearing on our computer is seen below:

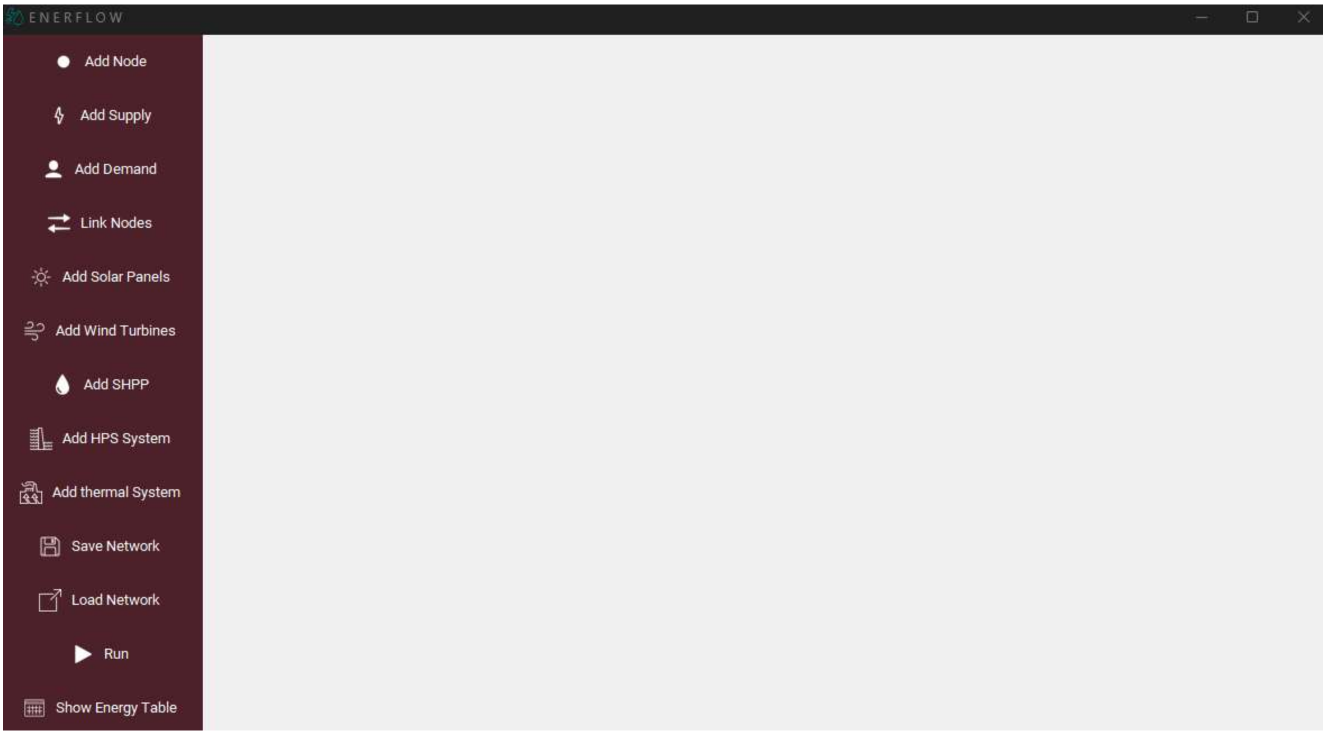


Figure 6.1 Starting screen of Enerflow

On the left side are the components to be used. Simple nodes, solar panels, wind turbines, SHHPs, PHS systems, thermal units as well as the option to assign a demand or a supply time series to each node. On the right side, we see the surface in which we can design our true HRES. The user can create the connections between real nodes, by clicking on “Link Nodes” button. They can also save their network or load an already existing one by clicking on the corresponding buttons.

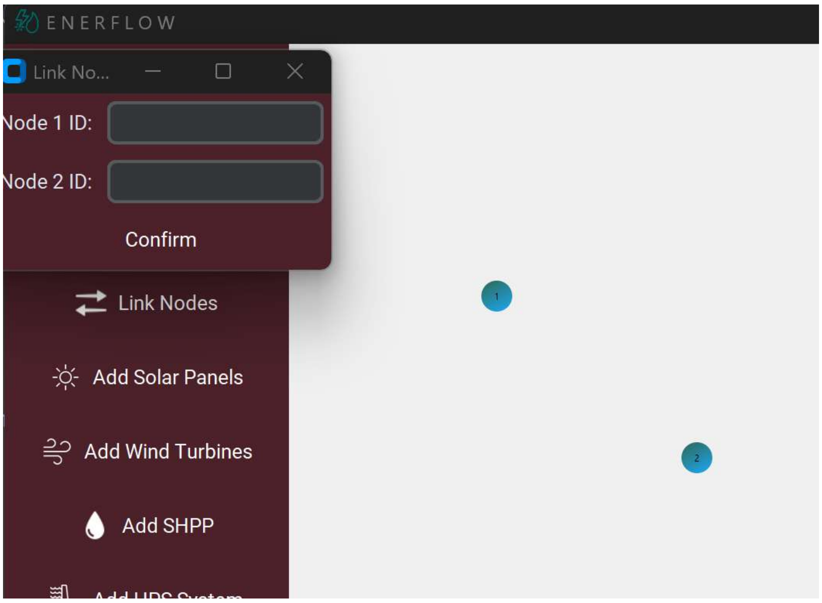


Figure 6.2 Link nodes window

By right - clicking on each added component, we can input the essential data for each one. For example, when solar panels are added we should add the radiation and temperature time series, as well as the other parameters addressed to, above. The time series should be text files (.txt) and we can browse them through our computer files.

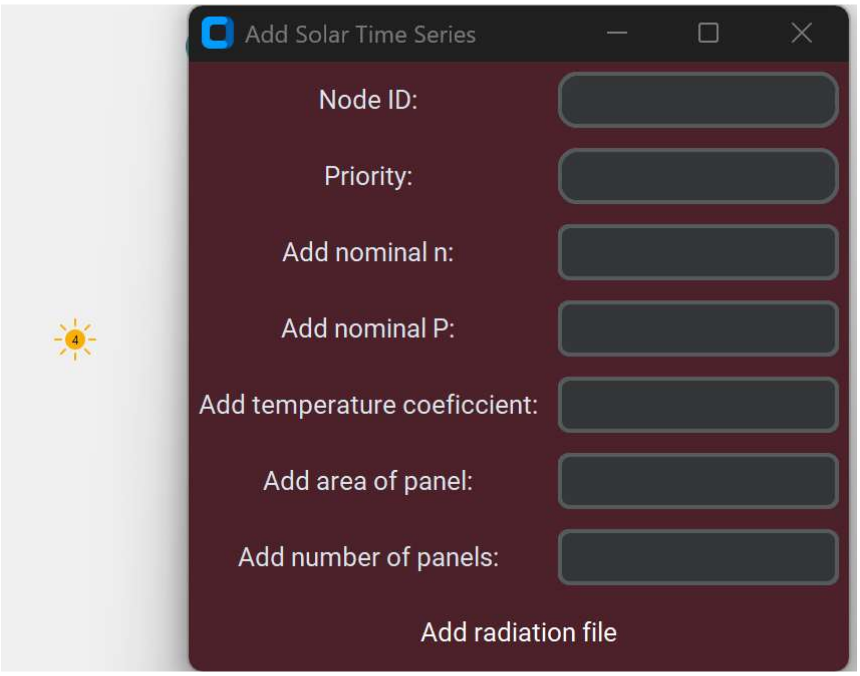


Figure 6.3 Inserting data for solar panels

To start the simulation, i.e. create the virtual system and find the optimal energy flows, we have to click on "Run" button. Then the virtual network created appears on our screen.

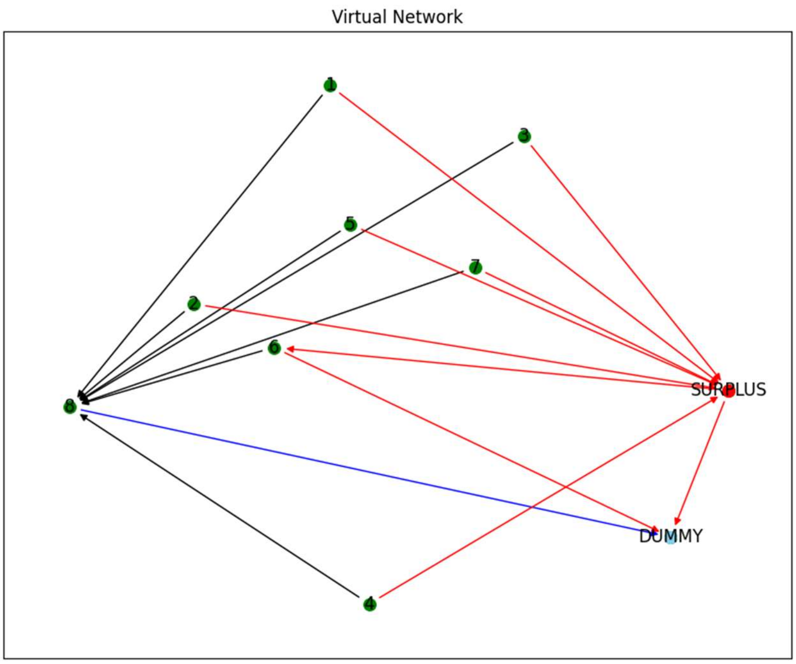


Figure 6.4 Example of virtual network appearing when running the software

At the end of the simulation, we can choose to present and plot the results in a table by clicking on “Show Energy Table” button.

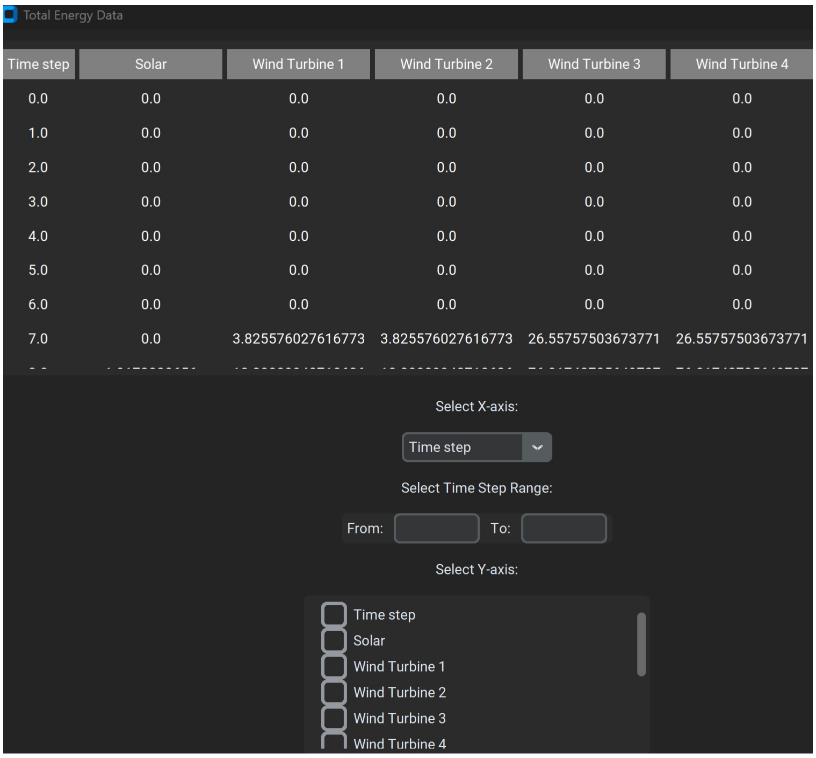


Figure 6.5 Plotting output data

7. Case study

7.1 General information

The case study being examined pertains to the island of Sifnos, a small island in the Cycladic complex with an area of 74 km^2 and a permanent population of 2,755 inhabitants, while the island attracts up to 100,000 tourists every summer. Sifnos is traversed by four parallel mountain ranges, with the main peaks reaching altitudes of 682 m and 463 m.

As Sifnos in a non-interconnected island (NII), locals established the Sifnos Island Cooperative (SIC), with main purpose to claim the island's energy independency as electric power is currently produced by the autonomous local power station consisting of diesel generator at an excessive cost. The annual electricity demand in Sifnos is about 17.5 GWh while there is a small 1.2 MW wind park and two photovoltaic parks of 0.203 MW power. According to energy analysis of the island for the year 2023 approximately 2.36 MWh were produced from the established RES (HEDNO, 2023).

7.2 Proposed system outline

Katsaprakakis and Voumvoulakis (2018) performed a preliminary study for Sifnos' system composed of wind turbines, solar panels and a pumped-storage system. All the components of the hybrid energy system are going to be installed in a single site. The upper reservoir of the PHS will be constructed on a ridge with an altitude of, approximately, 344 m. In this study, excavating a 1,100,000 m^3 reservoir is suggested, which is considered to be an enormous work for this size of island.

Zisos et al. (2023) proposed another scenario of a smaller-scale project through optimization with the reservoir's capacity being 315,195 m^3, four wind turbines (two of 2.3 MW nominal power each and two of 0.9 MW nominal power each) and 2 MW installed solar power.

7.2.1 Wind turbines

To utilize the available wind energy, we include two different wind turbines, the key characteristics of which are shown in Table 7.1:

Wind turbine type	Enercon E-44	Enercon E-70 E4
Rated power (kW)	900	2300
Minimum power (kW)	4	2
Cut-in wind speed (m/s)	3	2.5
Rated wind speed (m/s)	16.5	15.0
Cut-out wind speed (m/s)	34.0	34.0
Survival wind speed (m/s)	59.5	-
Tower height (m)	55	113

Table 7.1 Wind turbines' key characteristics

Moreover, Figure 7.1 and Figure 7.2 depict the manufacturer's power curves for the two turbine types.

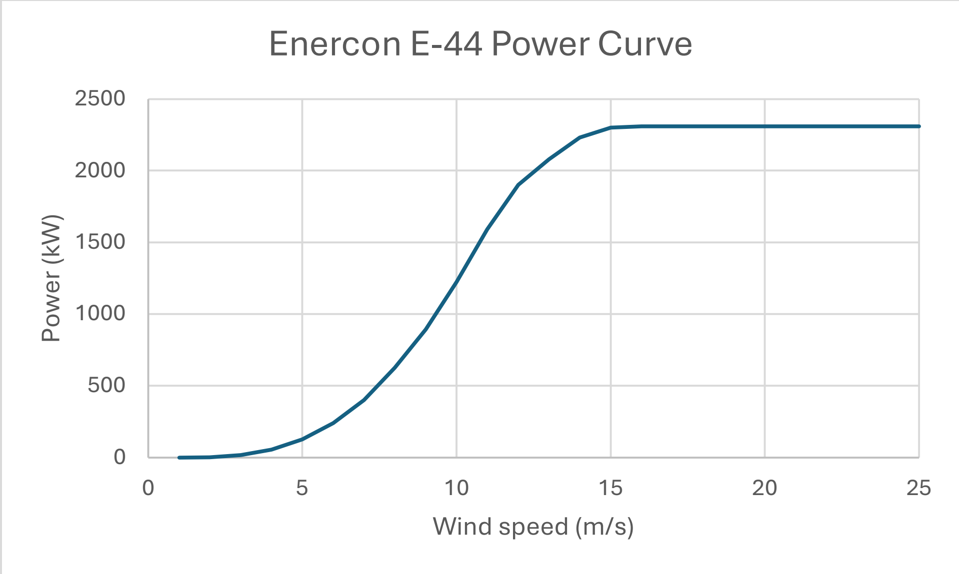


Figure 7.1 Enercon E-44 power curve

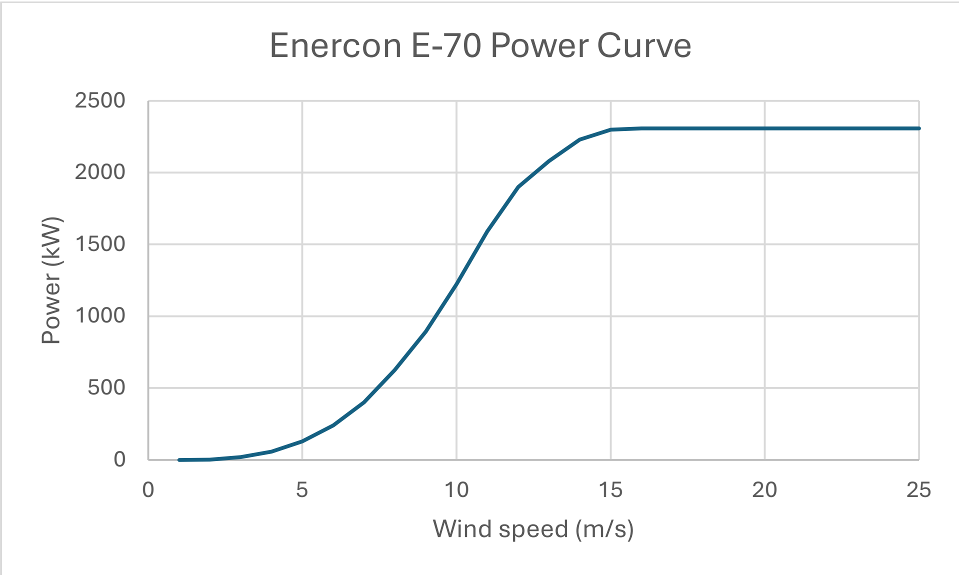


Figure 7.2 Enercon E-70 power curve

The input data are given below:

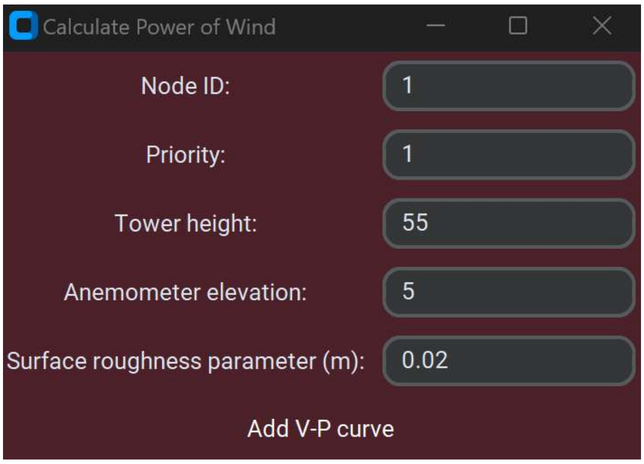


Figure 7.3 Input data for Enercon E-44

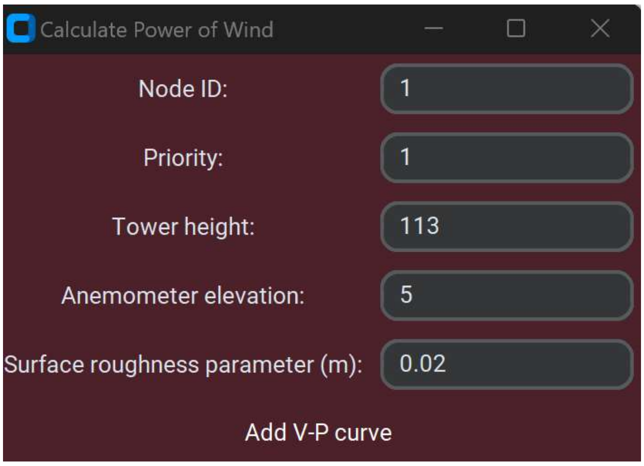


Figure 7.4 Input data for Enercon E-70 E4

The wind time-series are shown below:

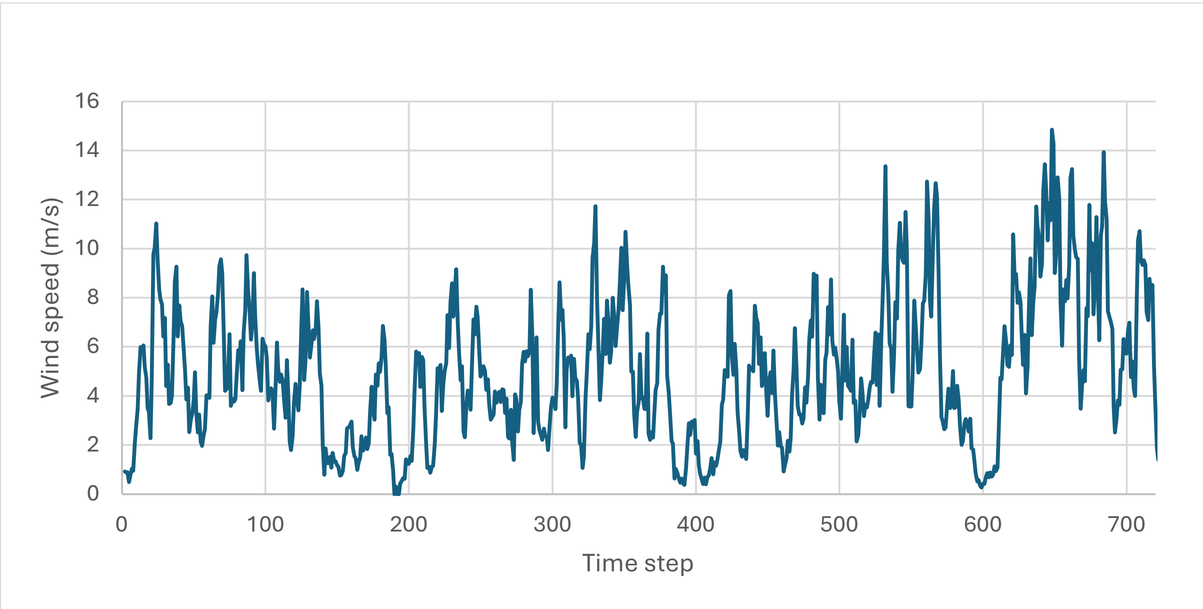


Figure 7.5 Wind speed time series for one month

7.2.2 Solar panels

The system, as optimized by Zisos et al. (2023), includes 4718 photovoltaics of rated 410 W rated power and of 1.94 m^2 panel surface each. The user inputs are seen below:

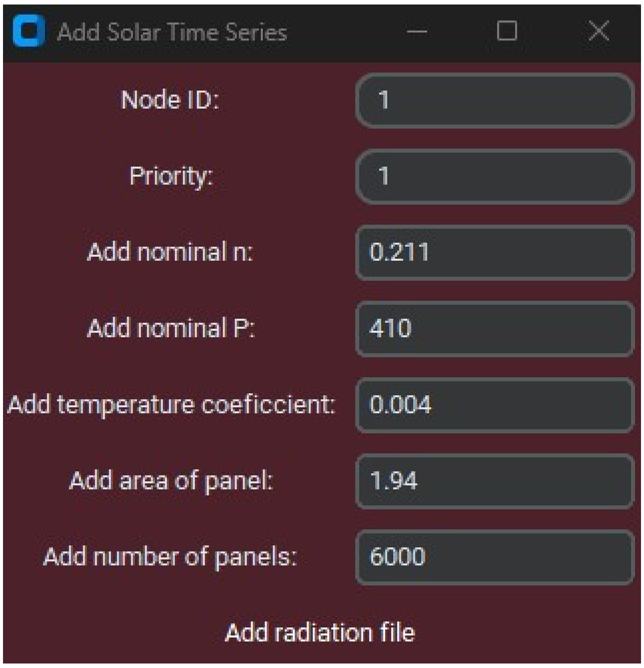


Figure 7.6 Input data for solar panels

Subsequently, we input the radiation and temperature time series, which are seen below:

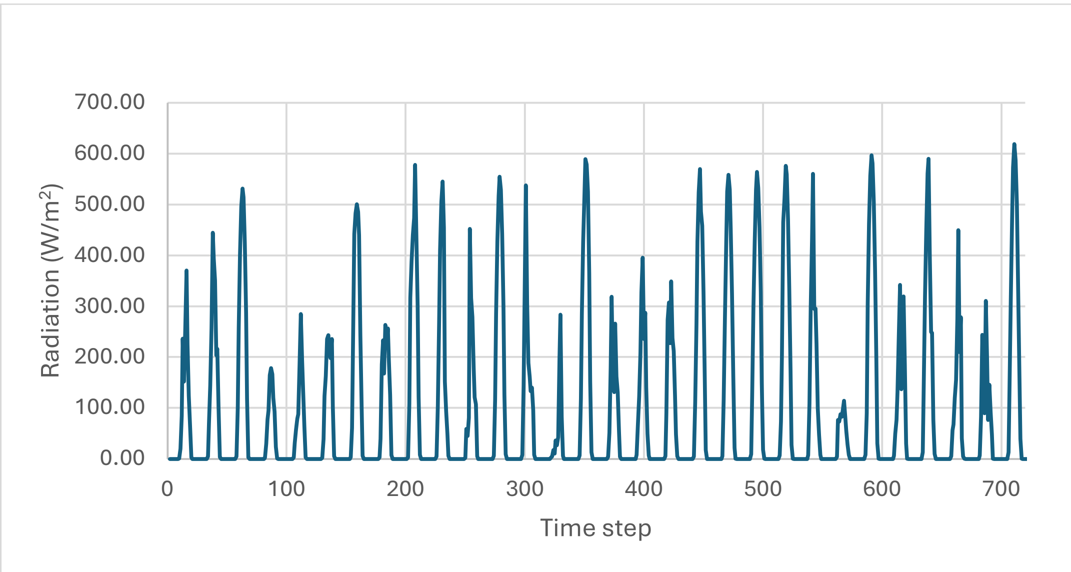


Figure 7.7 Radiation time series for one month

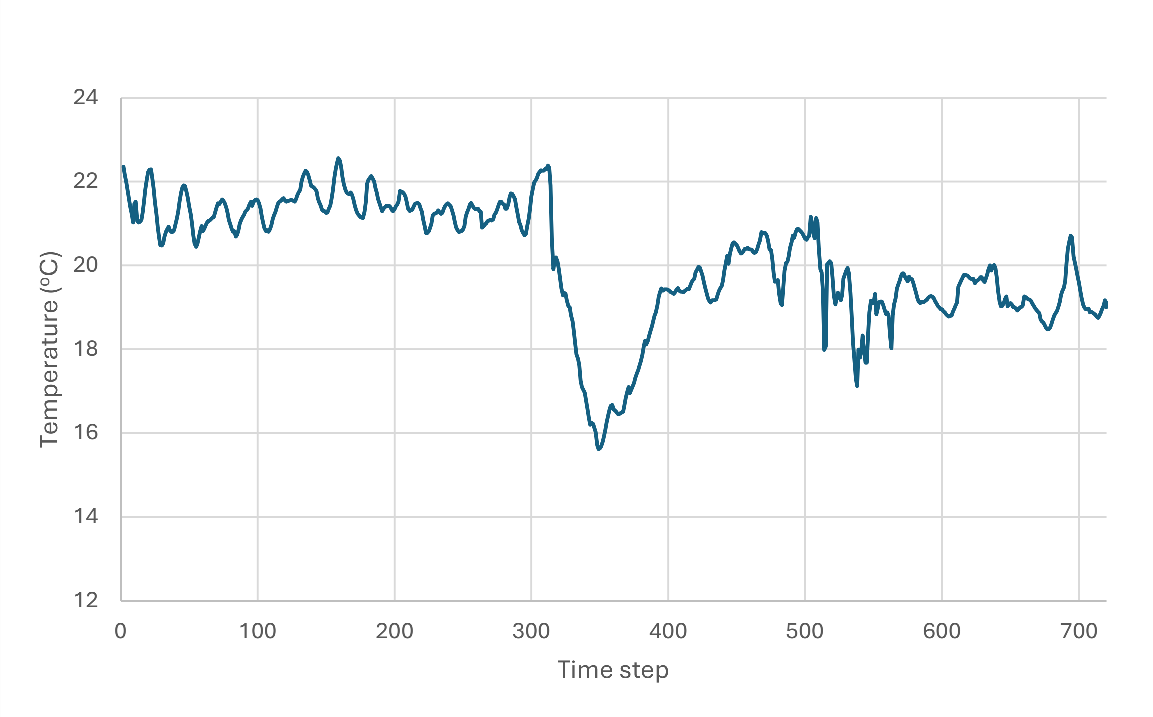


Figure 7.8 Temperature time series for one month

7.2.3 Thermal units

Sifnos' electricity generation currently depends on nine diesel – fuelled generators. The nominal power is 1,200 kW. For this case study, we ignore the ability of the generators to operate at a lower power and we open as many as need on their nominal power. The problem of how many and in which order should open is another optimization/ management product. We also consider a ramp-up time and ramp-down time equal to three hours and a minimum close time equal to six hours.

8. Results

We run the simulation for twenty years, in order to have a more comprehensive view on hybrid system's efficiency. We opt for two basic scenarios, one without a back-up oil-fuelled generator and one where nine units of a conventional generator can link to system to cover for unmet demands. To complete our study, it is necessary to examine altered parameters and scenarios to achieve a more thorough and comprehensive picture.

8.1 Energy production outputs

After inputting the essential data for each component, we get the hourly production as an output. The outputs for wind turbines and solar panels are seen below:

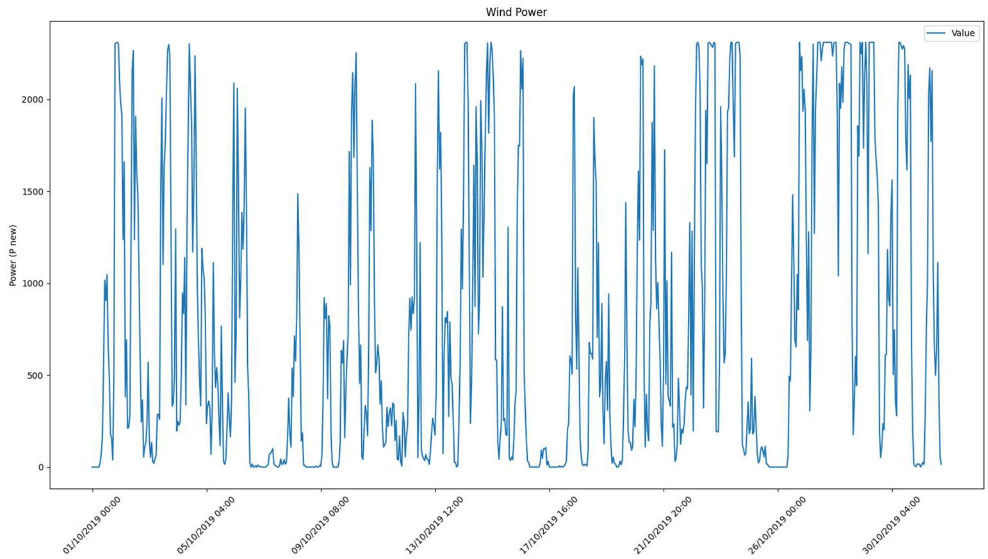


Figure 8.1 Enercon's E70 energy production

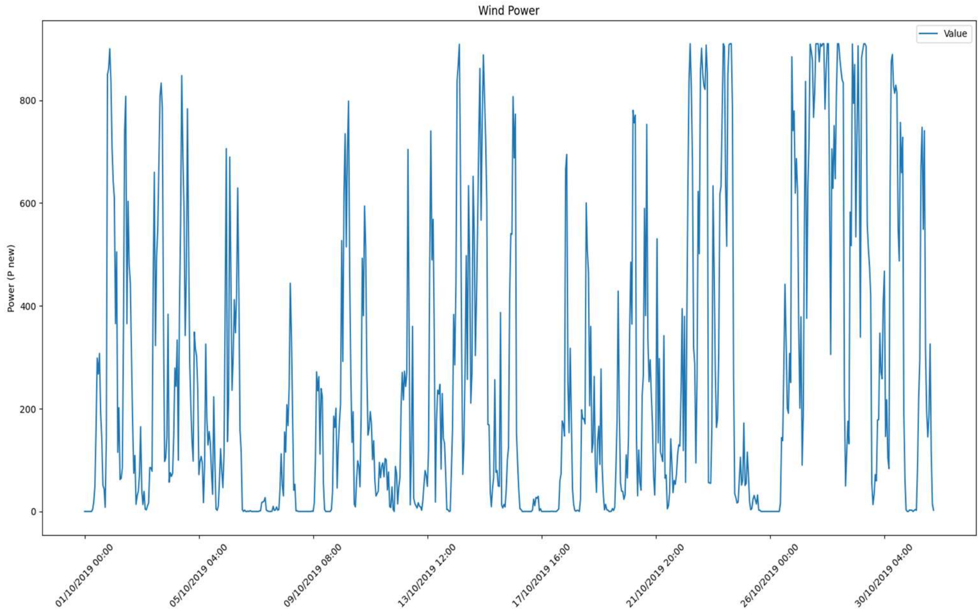


Figure 8.2 Enercon's E44 energy production

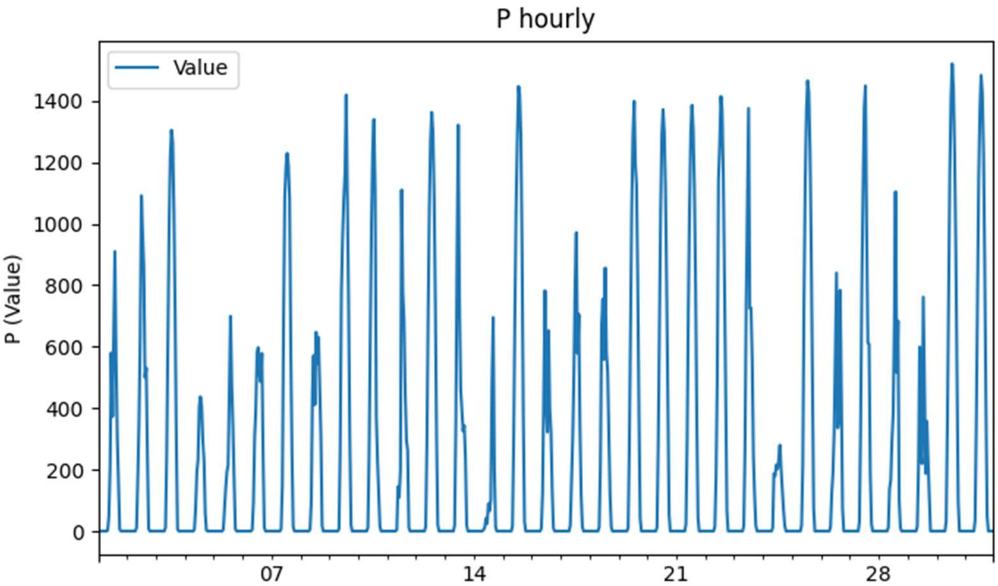


Figure 8.3 Solar panels' energy production

8.2 Scenario 1: HRES without thermal unit

For this scenario, we create the system being referred to above, without the use of thermal units. In fact, under these conditions the island of Sifnos will be powered only by renewable energy sources. The scenario's main features and simulation results are summarized in the table below:

Table 8.1 Scenario's 1 results

	Scenario 1
Installed Wind Power (MW)	6.4
Installed Solar Power (MW)	2.4
Mean annual energy from renewables (GWh)	19.5
Mean annual energy from PHS (GWh)	5.18
Mean annual energy stored (GWh)	8.2
Mean annual demand (GWh)	15.7
Reliability (%)	90%
Mean annual deficit (GWh)	1.9

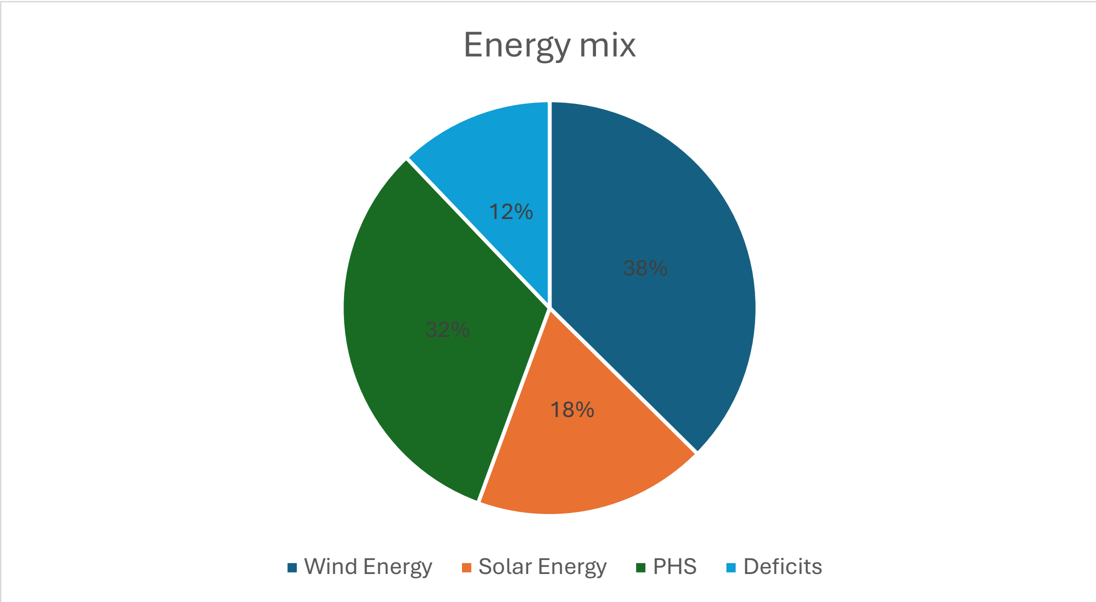


Figure 8.4 Energy mix for scenario 1

As shown, reliability is quite low, given the fact that energy demand must be met at all costs. However, mean annual deficit is considered small and a light change in RES components can mark a big difference.

Figure 8.5 depicts the hourly allocation of energy sources and demand throughout a typical month.

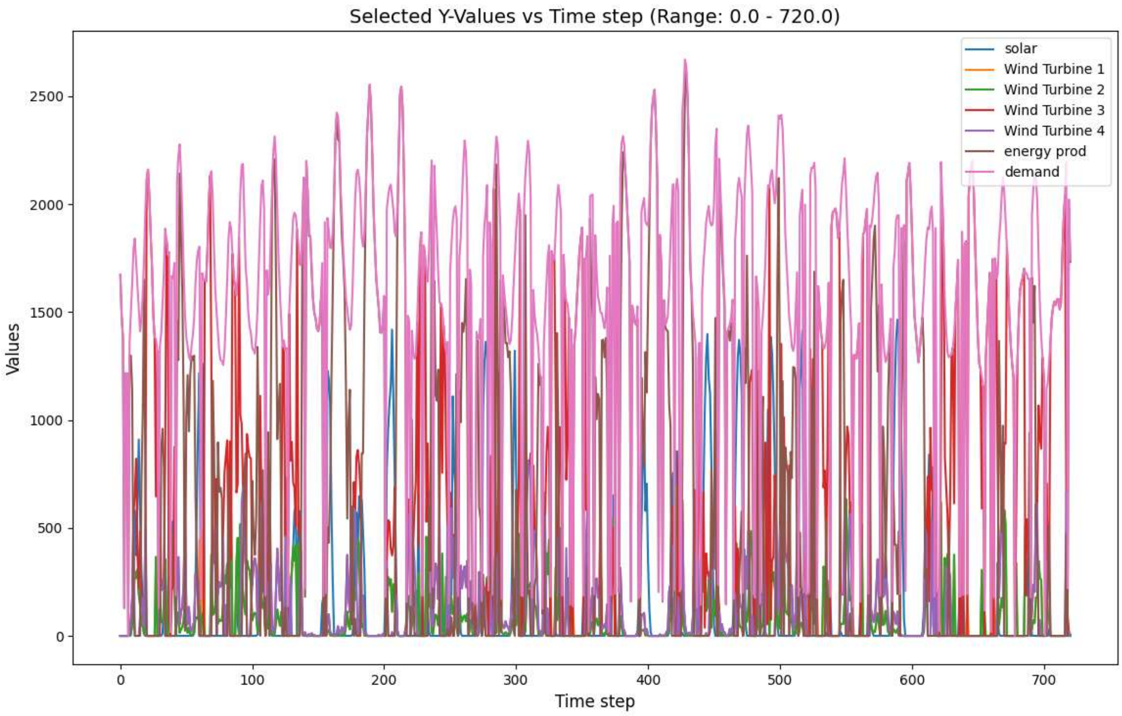


Figure 8.5 Hourly allocation of sources and demand (throughout a month)

Moreover, it is important to represent the upper reservoir's storage fluctuation throughout the years. We notice that the PHS system works adequately, as it both stores energy in the form of water in times of surplus and produces energy, by letting water flow through the turbine in times of deficits.

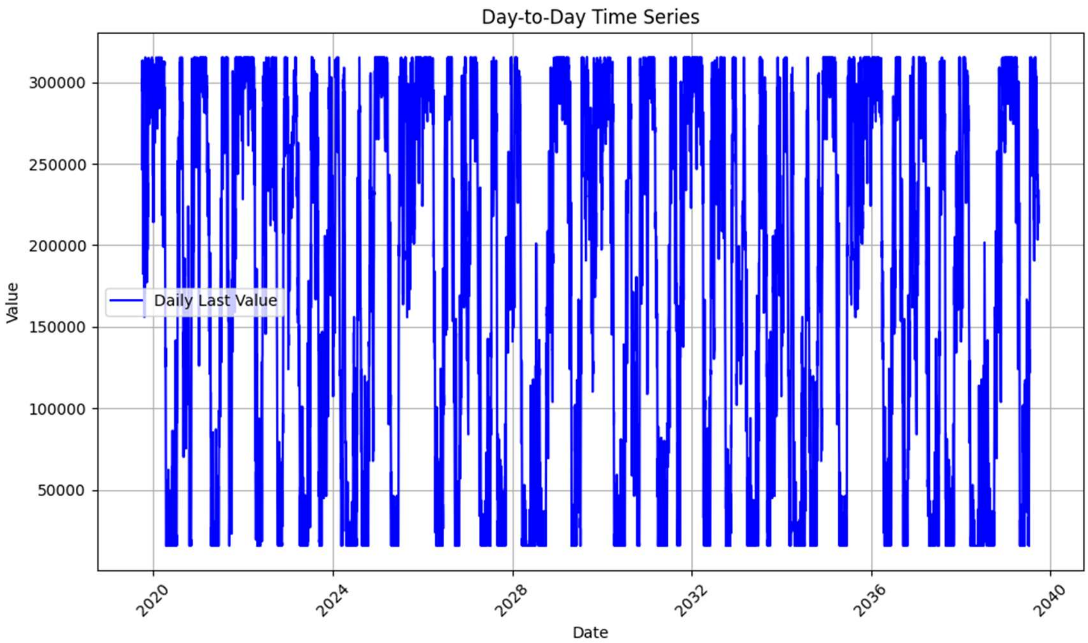


Figure 8.6 Daily upper reservoir's storage, scenario 1

8.3 Scenario 3: HRES with thermal unit

As mentioned before, thermal units are introduced into an HRES as a back-up, and used when the other sources cannot cover the deficits. After running the simulation for twenty years with the same data used in Scenario 1, we conclude that thermal unit can cover every deficit, and the reliability increases to 100%.

Table 8.2 Scenario's 2 results

	Scenario 2
Installed Wind Power (MW)	6.4
Installed Solar Power (MW)	2.4
Mean annual energy from renewables (GWh)	19.5
Mean annual energy from PHS (GWh)	5.7
Mean annual energy stored (GWh)	8.7
Mean annual demand (GWh)	15.7
Mean annual energy from thermal unit (GWh)	2.5
Reliability (%)	100%
Mean annual deficit (GWh)	0

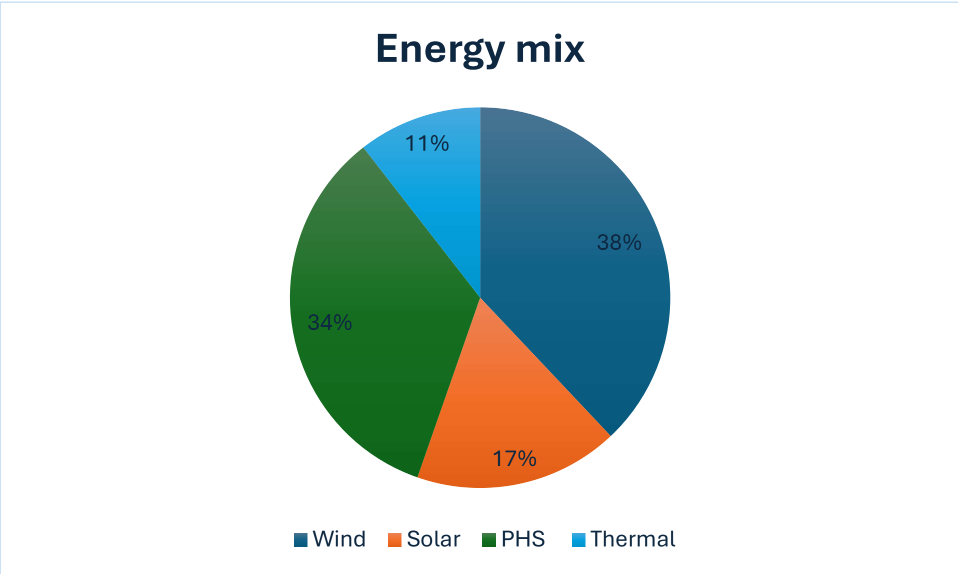


Figure 8.7 Energy mix of Scenario 2

Scenario 2 compared to Scenario 1 is definitely more reliable and safer, however it presupposes that diesel–fuelled generators are used, with the corresponding consequences as regard to high prices and environmental issues.

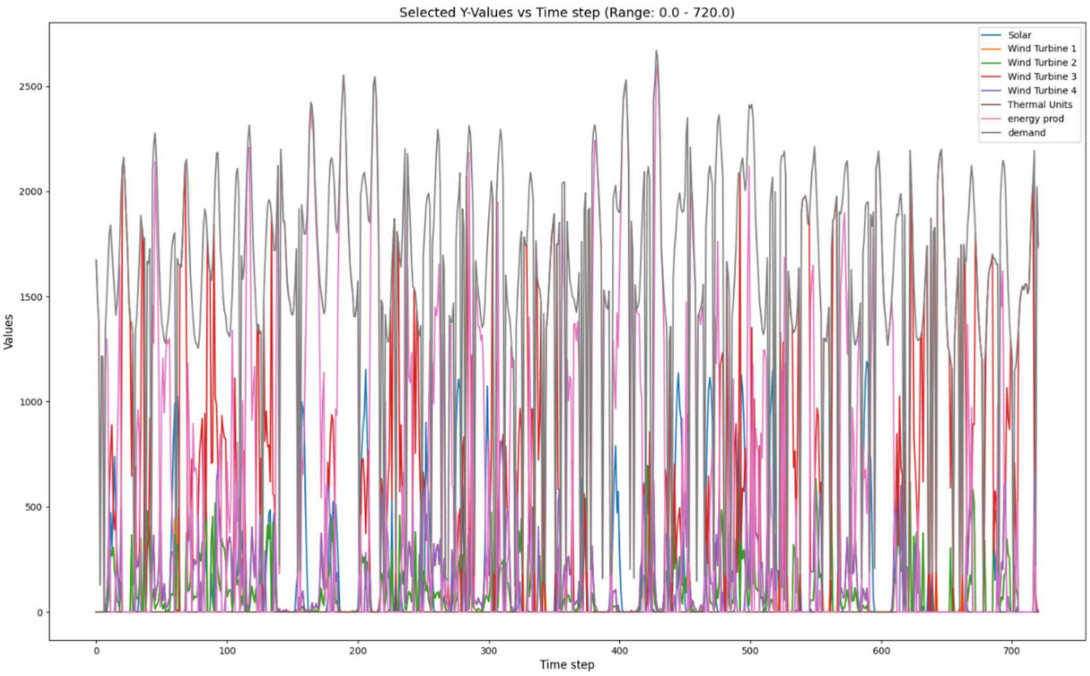


Figure 8.8 Hourly allocation of sources and demand (throughout a month)

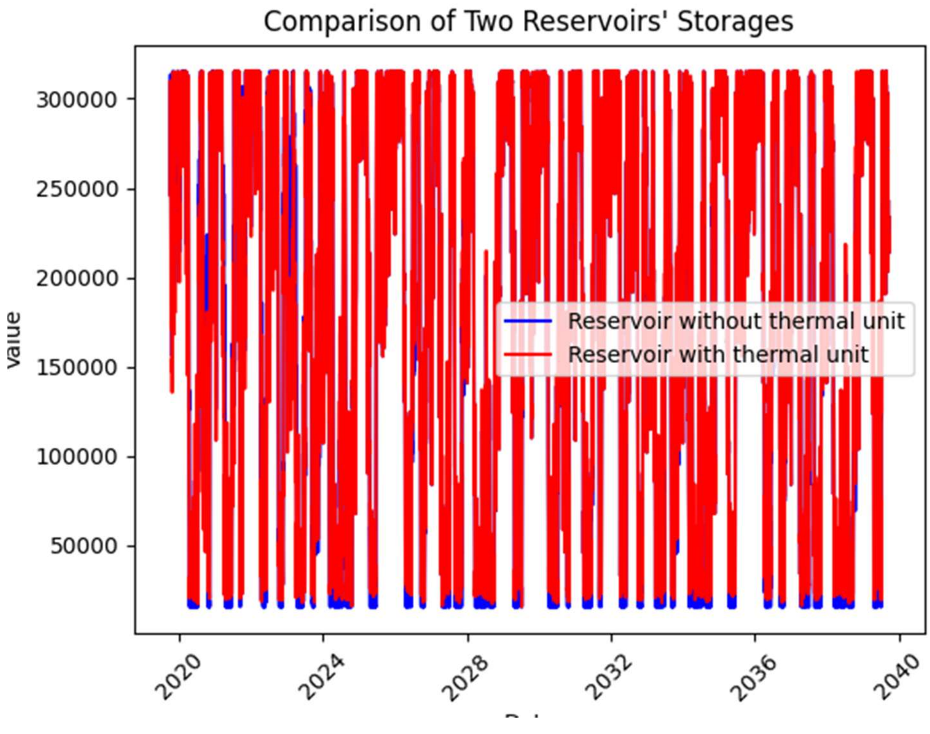


Figure 8.9 Comparison of two reservoirs

In Figure 8.9, the storages of the upper reservoirs in scenarios 1 and 2 are compared.

One can easily deduce that, while thermal units are integrated into the system, the reservoir keeps its storage at higher levels. This is since thermal units do not offer the exact energy needed to cover the shortfall, but operate at a maximum level, and even in times of no deficit in order to ensure that minimum operating and closing times are kept. As a result, this surplus energy is used to pump and store water for future utilization.

8.4 Integration of more wind turbines

With the aim of presenting a sustainable solution without the integration of thermal units, we tested some alternative scenarios to enhance reliability while maintaining the maximum environmental sustainability of the energy footprint.

In this scenario, we add one more large wind turbine (of 2.3 MW) to the baseline HRES. The results of this trial are shown below:

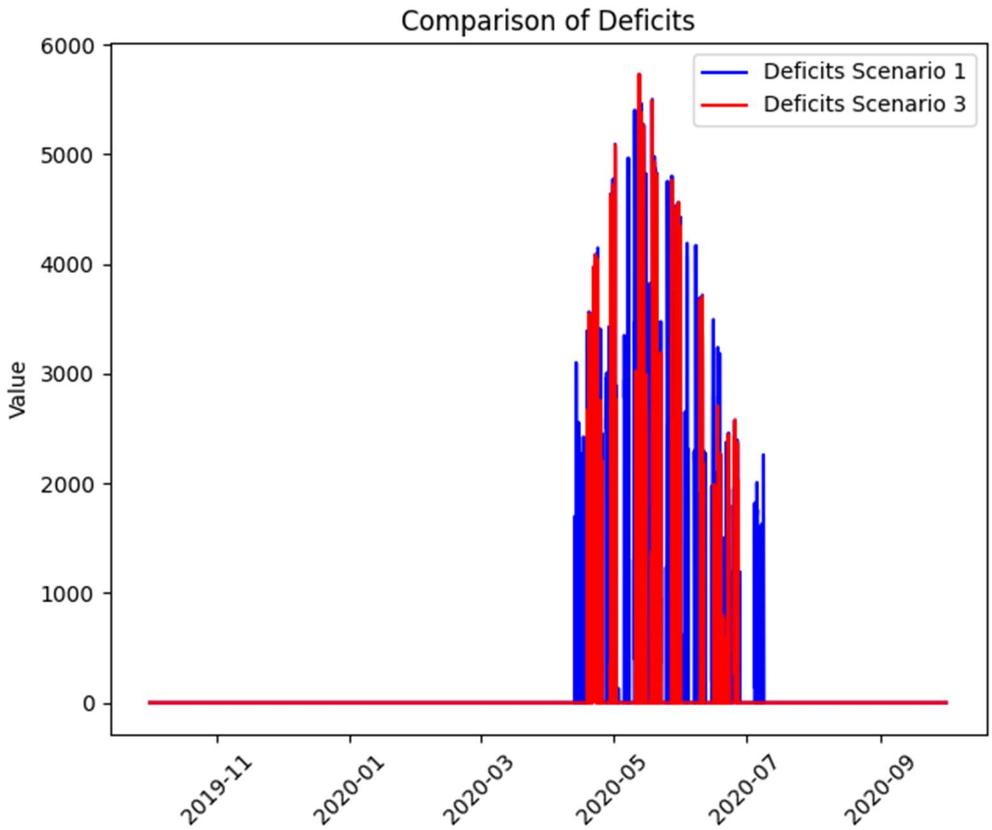


Figure 8.10 Deficits at Scenarios 1 and 3

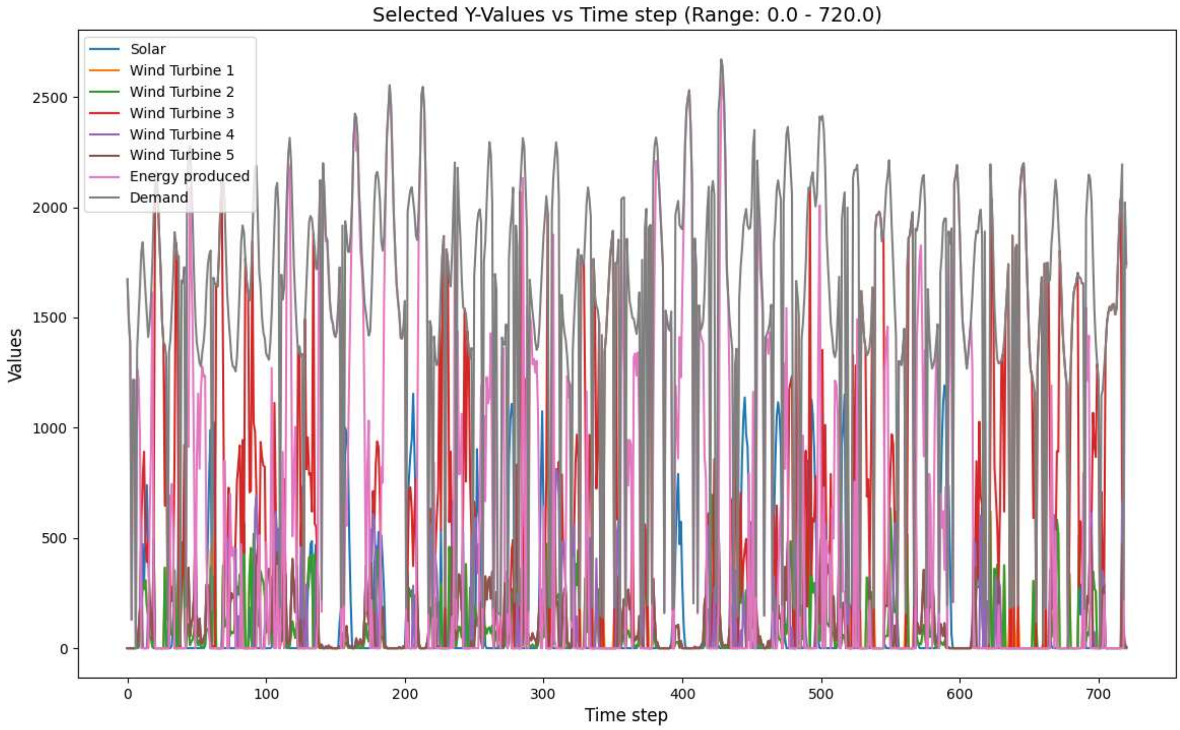


Figure 8.11 Hourly allocation of sources and demand (throughout a month)

8.5 Experimenting with upper reservoir's storage capacity

In order to reveal the software's capabilities, we investigate how the modification of a particular system component influences the outcomes of the simulation. Thus, we experimented with different upper reservoir's storage capacity values, as it is considered a crucial design variable from both a technical and financial perspective, and the operation or not of the thermal to understand this variable's sensitivity. We show the results for both.

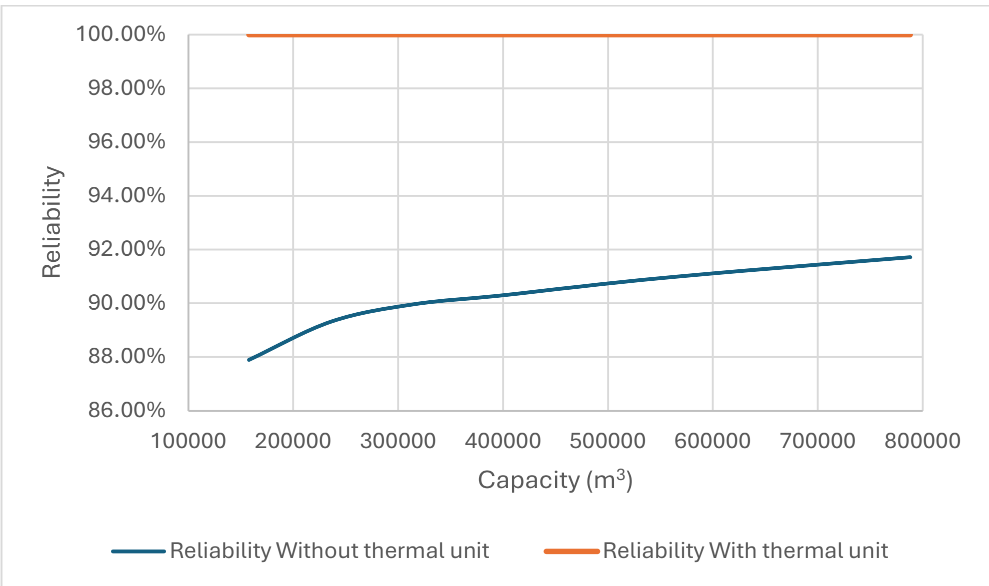


Figure 8.12 Reliability - capacity relationship with and without thermal units

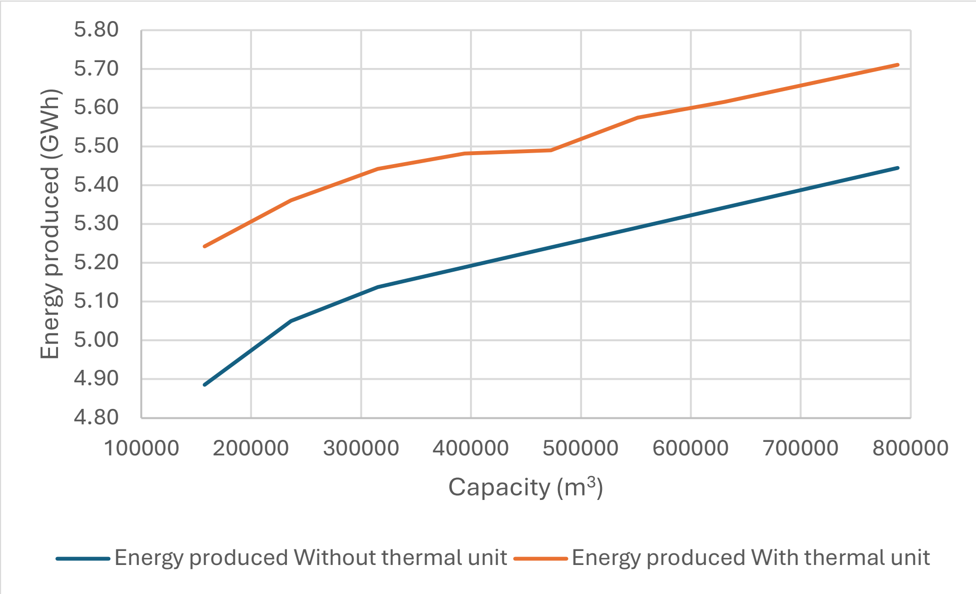


Figure 8.13 Energy produced - capacity relationship with and without thermal units

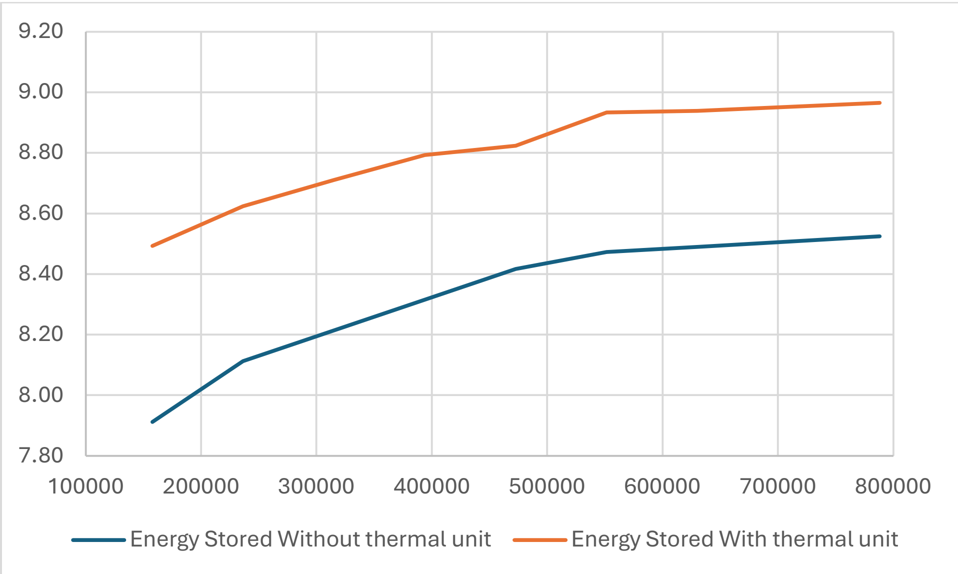


Figure 8.14 Energy stored - capacity relationship with and without thermal units

We conclude that by increasing the reservoir's capacity, the system's reliability, energy production and storage increase too. However, the growth rate slows down after 315,195 m^3, raising questions about the viability of a further increase.

It is of great interest to examine the results of the thermal unit's production. We notice that thermal production, and consequently the cost, decreases while storage capacity increases, which leads to less environmental impacts and reduced financial costs.

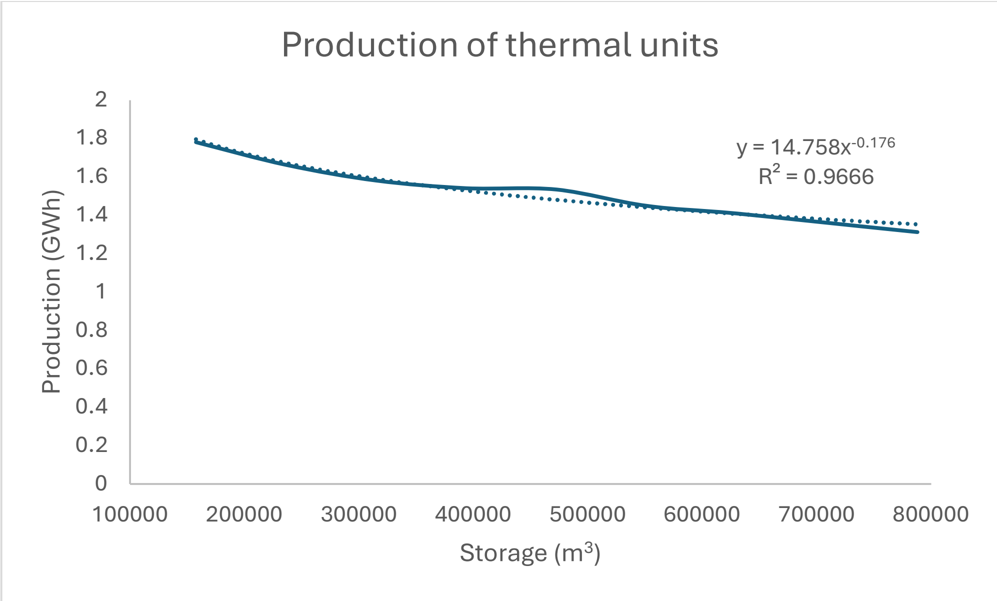


Figure 8.15 Energy production of thermal unit

9. Conclusions

9.1 Synopsis and conclusions

Triggered by the methodological advances and computational capabilities of Hydronomeas, the aim of this thesis was to develop a generic methodology and associated software that will simulate the optimal energy flow across HRES systems of any topology.

Firstly, we introduced the concepts of hybrid renewable energy systems and emphasized on calculating energy production from each component, with basic inputs to be technical characteristics and meteorological data. This alone, is a useful tool as computations are done quickly and in an effective manner.

A breakthrough is the introduction of conventional thermal units to the system which makes the situation much more complicated as they operate under a variety of technical constraints, such as the minimum close time, the ramp – up time, the fact that they cannot be instantly connected to the system but need a few hours to produce energy. All the above are considered and successfully performed in *Enerflow.*

Overall, we proceeded to build the optimal energy flow simulation problem under the network linear programming framework, thus representing all system's elements as a graph, and defining its properties by means of vectors, to which dynamic capacities, costs, demands and supplies are assigned. Under this premise, the optimal distribution of energy flows is estimated by minimizing the total transhipment cost across the graph.

All background computational procedures were fully automatized within *Enerflow*, which eventually allows to export all simulation results in an excel file.

Following this, we tested *Enerflow* on a real case study of Sifnos, a Greek island aiming to be completely energy-independent by 2030. The evaluation came across two basic scenarios, i.e. a fully autonomous configuration, without conventional sources, and a more realistic one, containing diesel generators. We noticed a large difference in the reliabilities of the two scenarios altering from 90% to a perfect 100%.

Finally, we investigated alternative scenarios and particularly focused on the behaviour of the system while modifying the upper reservoir's capacity. We noticed small differences in terms of reliability when increasing capacity, event that prompts inquiries over the viability of an additional expansion.

Conclusively, we can state that *Enerflow* offers a twofold service. First and foremost, it can be used for the long-term planning of hybrid renewable energy systems and support the design of their critical infrastructures (e.g. Sifnos' case). With the basic data available, by means of hydrometeorological and inputs and power demands, one can experiment with different hybrid system layouts, estimate the associated costs and benefits, evaluate their reliability etc.

The second service involves the operational problem, namely the optimal allocation of energy fluxes in the short-term (e.g., day-ahead). In this vein, *Enerflow* may be used as a prediction tool, providing valid forecasting of energy surpluses and deficits, thus making renewable energy management more efficient and easier. In this vein, *Enerflow* should get its inputs by forecasting systems (for the weather and the energy demand), and provide updated predictions as more information are available.

9.2 Future research objectives

One should think of *Enerflow*, as a dynamically evolving entity, constantly developing and changing, with a view to improving and adapting to possible new needs. Given this dynamic nature, there is always room for improvement. Most specifically, from a technical perspective:

- The code behind the software should be optimized, to minimize the computational load.
- A better linear optimization solver can be introduced, which will also mark significant changes in the speed of computational.

Moreover, it is crucial to embed within the optimization procedure both design elements and management rules for the energy production and storage components, towards providing a decision-making tool instead of a simulation model per se.

Finally, the most ambitious step is the introduction of hydropower and other water-energy components to the system, e.g. reservoirs that will serve both hydrological and energy goals. The simultaneous management of water and energy flows introduces major complexities and is surely an interesting path to explore.

As science marches towards the unknown the journey of knowledge knows no destination. This research aims to be a small stone in the academic quest, opening paths for new questions and answers.

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