A stochastic simulation framework for representing water, energy and financial fluxes across a non-connected island

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SCHOOL OF CIVIL ENGINEERING

DEPARTMENT OF WATER RESOURCES & ENVIRONMENTAL ENGINEERING

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ΕΥΧΑΡΙΣΤΙΕΣ / [ACKNOWLEDGEMENTS]

Η εκπόνηση και παρουσίαση της παρούσας διπλωματικής σηματοδοτούν το τέλος της φοίτησης μου στη σχολή Πολιτικών Μηχανικών ΕΜΠ και την απαρχή ενός νέου κεφαλαίου στη ζωή μου. Σε αυτήν την κομβικής σημασίας περίοδο της ζωής μου, συγκεκριμένοι άνθρωποι με στήριξαν συμβάλλοντας στην εκπόνηση της παρούσας εργασίας και νοιώθω πολύ έντονη την ανάγκη να τους ευχαριστήσω.

Πρωτίστως, θα ήθελα να ευχαριστήσω τον επιβλέποντα κ. Ανδρέα Ευστρατιάδη για τη σύλληψη και ανάθεση ενός θέματος ξεχωριστού ενδιαφέροντος όπως αυτό της προσομοίωσης χρηματιστηρίου ενέργειας στο Υβριδικό Σύστημα Ενέργειας της νήσου Ικαρίας. Πολλώ δε μάλλον, θα ήθελα να τον ευχαριστήσω γιατί με το πάθος του και την αστείρευτη όρεξη του καταφέρνει να εθίσει τους φοιτητές του στο αντικείμενο του Υδραυλικού Μηχανικού και να τους εμπνεύσει να ασχοληθούν εκτενέστερα με αυτό. Ακόμη, του οφείλω ένα μεγάλο ευχαριστώ για τον χρόνο που διέθεσε σε συνεχείς συναντήσεις και συζητήσεις πάνω στο αντικείμενο της εργασίας καθώς και για την ανοχή και την υπομονή που επέδειξε στις ανακρίβειες και τις αστοχίες μου κατά τη διάρκεια της εκπόνησης της εργασίας. Οφείλω να επισημάνω ότι καθ’ όλη την επαφή μας κατά τη διάρκεια της φοιτητικής μου ζωής κατάφερε να ενεργοποιήσει την ερευνητική μου διάθεση, με βοήθησε να διαμορφώσω κριτική στάση απέναντι στα προβλήματα που αντιμετωπίζει ένας μηχανικός και, εν συνόλω, συνεισέφερε τα μέγιστα στην ανάπτυξη νέων πτυχών της προσωπικότητας μου. Τέλος, με το ήθος του και το διδακτικό του έργο αποτελεί αδιαμφισβήτητα ένα μεγάλο κεφάλαιο για τη σχολή Πολιτικών Μηχανικών ΕΜΠ και του εύχομαι να συνεχίσει στο μέλλον ανάλογο έργο, καθώς η σχολή και ιδιαίτερα η φοιτητική κοινότητα έχουν ανάγκη καθηγητές και ανθρώπους σαν τον κ. Ευστρατιάδη.

Ακόμη, θα ήθελα να ευχαριστήσω θερμά τον κ. Νικόλαο Μαμάση, Αναπληρωτή Καθηγητή ΕΜΠ, για τις πολύ χρήσιμες συμβουλές του σε θέματα που αφορούσαν την εργασία, καθώς και για τον χρόνο που αφιέρωσε σε αυτήν.

Επίσης, οφείλω ένα μεγάλο ευχαριστώ στον Δρ. Ιωάννη Τσουκαλά για την συνεισφορά του στην εκπόνηση της παρούσας εργασίας. Συγκεκριμένα, με την ανάπτυξη του μοντέλου πρόβλεψης ταχύτητας ανέμων από πλευράς του κ. Τσουκαλά κατέστη δυνατή την προσομοίωση του χρηματιστηρίου ενέργειας του νησιού σε πραγματικό χρόνο και χωρίς αυτό δεν θα ήταν ποτέ δυνατή η ολοκλήρωση της εργασίας.

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ερωτήματα σχετικά με τη διάρθρωση αυτού και να διαμορφώσει τη βέλτιστη λειτουργία του.

Σε αυτό το σημείο θα ήθελα να κάνω μία ιδιαίτερη αναφορά στο φίλο και συμφοιτητή μου Πέττα Αντώνιο-Γενναίο, με την συνεισφορά του οποίου κατέστη δυνατή η φετινή μας παρουσία στο συνέδριο EGU 2019. Ο Γενναίος με το ερευνητικό του πνεύμα, το εύρος των γνώσεων του, την κριτική του στάση απέναντι στο πρόβλημα που κληθήκαμε να αντιμετωπίσουμε και την ευχάριστη παρουσία του κατάφερε να μετατρέψει την προετοιμασία μας για τη συμμετοχή στο συνέδριο σε μία πολύ ιδιαίτερη εμπειρία.

Κλείνοντας, όσο κλισέ και αν ακουστεί, θα ήθελα να ευχαριστήσω τους φίλους και την οικογένεια μου για την υλική και πνευματική τους συνεισφορά κατά τη διάρκεια των φοιτητικών μου χρόνων, για την πίστη τους στις δυνατότητες μου αλλά και την ανοχή τους στις ιδιοτροπίες μου.

Μαυριτσάκης Παναγιώτης

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ABSTRACT

Integrated modeling of hybrid water-energy systems, comprising multiple energy sources, conventional and renewable, pumped-storage facilities and other hydraulic infrastructures, which aim to serve combined water and energy uses, is a highly challenging problem. On the one hand, such systems are subject to significant uncertainties that span over all associated inputs, physical and anthropogenic, i.e., hydrometeorological processes and water-energy demands, respectively. On the other hand, their everyday operation is subject to multiple complexities, due to the conflicting uses, constraints and economic interests. Taking as example a future configuration of the electric system of Ikaria Island, Greece, we demonstrate a stochastic simulation framework, comprising: (a) a synthetic time series generator that reproduces the statistical and stochastic properties of key input processes (i.e., reservoir inflows and wind speed) at multiple temporal scales; and (b) a simulation module employing the hourly operation of the system, to estimate the associated water, energy and financial fluxes. In this context, several problems are examined, under alternative policies and assumptions. Generally, these can be classified into two categories, i.e. the optimal design of key system components, and the real-time operation of a hypothetical energy market, involving three energy providers and associated electricity sources, i.e. hydroelectric, wind power, and thermoelectric.

Εκτενής Περίληψη / [Extended Abstract in Greek]

Αντικείμενο της παρούσας εργασίας αποτελεί η μοντελοποίηση και βελτιστοποίηση του Υβριδικού Συστήματος Ενέργειας (ΥΒΕ) της μη διασυνδεδεμένης με το ηπειρωτικό δίκτυο Ικαρίας και η προσομοίωση ενός υποθετικού χρηματιστηρίου ενέργειας για την κάλυψη των ενεργειακών απαιτήσεων του νησιού.

Οι εργασίες κατασκευής του έργου ξεκίνησαν το 2010 και ολοκληρώθηκαν τον Ιούνιο του 2019. Το παρόν έργο αποτελεί μέρος της προσπάθειας για επίτευξη των στόχων που έχουν τεθεί από το Πρωτόκολλο του Κιότο για την παραγωγή ενέργειας. Πιο συγκεκριμένα, το 1997 εγκρίθηκε το Πρωτόκολλο του Κιότο, το οποίο εισήγαγε νομικά δεσμευτικούς στόχους μείωσης των εκπομπών για τις ανεπτυγμένες χώρες. Η δεύτερη περίοδος δεσμεύσεων του Πρωτοκόλλου του Κιότο άρχισε την 1η Ιανουαρίου 2013 και λήγει το 2020. Σε αυτήν συμμετέχουν 38 ανεπτυγμένες χώρες, μεταξύ των οποίων η Ε.Ε. και τα 28 κράτη μέλη της.

Το Ευρωπαϊκό Συμβούλιο ενέκρινε μια ολοκληρωμένη προσέγγιση για την κλιματική και ενεργειακή πολιτική με στόχο την καταπολέμηση της αλλαγής του κλίματος και την αύξηση της ενεργειακής ασφάλειας της Ε.Ε., ενισχύοντας παράλληλα την ανταγωνιστικότητα της και την μετατροπή της σε μια ιδιαίτερα αποδοτική από ενεργειακή άποψη οικονομία χαμηλών εκπομπών άνθρακα.

Οι απαιτήσεις που υιοθετήθηκαν από τους αρχηγούς κρατών και κυβερνήσεων αφορούσαν στο ακόλουθο τρίπτυχο:

- Μείωση των εκπομπών των αερίων θερμοκηπίου κατά τουλάχιστον 20% κάτω από τα επίπεδα του 1990;
- 20% της κατανάλωσης ενέργειας της ΕΕ να προέρχεται από ανανεώσιμες πηγές;
- Μείωση κατά 20% στη χρήση πρωτογενούς ενέργειας σε σύγκριση με τα προβλεπόμενα επίπεδα μέσω τη βελτίωσης της ενεργειακής απόδοσης.

Οι παραπάνω απαιτήσεις είναι γνωστές ως στόχος «20-20-20».

Ιδιαίτερα στον νησιωτικό χώρο και, κυρίως, στα μη διασυνδεδεμένα νησιά, τα οποία έχουν αυτόνομους σταθμούς παραγωγής ηλεκτρικής ενέργειας, η διείσδυση εγκαταστάσεων διαφόρων μορφών Ανανεώσιμων Πηγών Ενέργειας (ΑΠΕ), όπως τα αιολικά πάρκα, οι φωτοβολταϊκοί σταθμοί και οι υδροηλεκτρικοί σταθμοί, μπορεί να καλύψει σημαντικό μέρος των αναγκών τροφοδότησης των καταναλωτών, μειώνοντας τις περιβαλλοντικές επιπτώσεις. Δεδομένου του υψηλού λειτουργικού κόστους των συμβατικών μονάδων παραγωγής στα απομακρυσμένα νησιά, λόγω του διογκωμένου κόστους μεταφοράς του καυσίμου και των περιβαλλοντικών φόρων, η διείσδυση των ΑΠΕ καθίσταται ακόμη πιο αναγκαία.

Παρόλα αυτά, τα επίπεδα αιολικής διείσδυσης στα ελληνικά νησιά παραμένουν ακόμη χαμηλά, παρά το υψηλό αιολικό τους δυναμικό, εξαιτίας των διάφορων προβλημάτων που εμφανίζουν τέτοιου είδους συστήματα παραγωγής ηλεκτρικής ενέργειας. Η στοχαστική φύση της παραγόμενης ισχύος των εγκαταστάσεων φωτοβολταϊκών και ανεμογεννητριών και η περιορισμένη δυνατότητά τους να ελέγχουν την ισχύ τους καθιστούν αμφίβολο το βαθμό αξιοπιστίας της λειτουργίας και απόδοσης τέτοιων εγκαταστάσεων στις απομακρυσμένες περιοχές. Η εξάρτηση των ΑΠΕ από τα φυσικά φαινόμενα έχουν ως αποτέλεσμα τη χρονική μεταβολή του ενεργειακού δυναμικού τους. Με τον κατάλληλο όμως τρόπο και τη σχεδίαση της λειτουργίας αυτών, καθώς και με τον συνδυασμό τους με άλλες μορφές ενέργειας, προκειμένου να αποθηκεύεται η περίσσεια της παραγωγής, είναι δυνατή η επίτευξη υψηλού βαθμού κάλυψης της ζήτησης σε ηλεκτρική ενέργεια σε περιοχές μη διασυνδεδεμένες με το δίκτυο διανομής της ηπειρωτικής χώρας.

Στο πλαίσιο, λοιπόν, αυτής της προσπάθειας, ξεκίνησε η υλοποίηση Υβριδικών Ενεργειακών Έργων (ΥΒΕ), όπως είναι αυτό της Ικαρίας, από την ΔΕΗ ΑΕ. Στόχος του έργου αυτού είναι η παραγωγή ενέργειας που θα βασίζεται στο συνδυασμό δύο διαφορετικών μορφών ΑΠΕ, ήτοι αιολικής και υδροηλεκτρικής, με αποθήκευση της πλεονάζουσας αιολικής ενέργειας μέσω αντλησιοταμίευσης. Πέραν των δύο παραπάνω μορφών ΑΠΕ, το Σύστημα Διαχείρισης Φορτίων του έργου θα ελέγχει την ισχύ των ντηζελογεννητριών του Σταθμού Αγίου Κηρύκου, τα φορτία κατανάλωσης, την στάθμη νερού στις δεξαμενές, και την ευστάθεια του ηλεκτρικού δικτύου του νησιού, εξασφαλίζοντας τη μέγιστη δυνατή κάλυψη των φορτίων κατανάλωσης του νησιού από ΑΠΕ.

Το συγκεκριμένο έργο είναι ένα από τα πρώτα του είδους στην Ευρώπη (πρώτο το ισπανικό νησί Ελ Ιέρρο), συνεπώς αποτελεί μία πρώτης τάξης ευκαιρία ελέγχου των πρακτικών αποθήκευσης και ελεγχόμενης διανομής της παραγόμενης ενέργειας. Επιπλέον, από την προσομοίωση του χρηματιστηρίου ενέργειας αναμένεται να προκύψουν σημαντικά πορίσματα σχετικά με την πολιτική της ενέργειας στο μη διασυνδεδεμένο δίκτυο.

Η προσομοίωση του υβριδικού ενεργειακού συστήματος της Ικαρίας περιλαμβάνει τέσσερις ανεμογεννήτριες και τρεις ταμιευτήρες με υδροστρόβιλους. Στο σύστημα ορίζονται κανόνες και περιορισμοί που έχουν τεθεί κατά την μελέτη με σκοπό τη διασφάλιση της αρδευτικής χρήσης νερού από τον ταμιευτήρα. Ζητούμενο της αναπαράστασης είναι η κατανόηση του τρόπου λειτουργίας του συστήματος αυτού και η συνεργασία των διάφορων μορφών ενέργειας που συμμετέχουν στην παραγωγή της επιθυμητής ηλεκτρικής ενέργειας, διατηρώντας σε υψηλότερη ιεραρχία την αρδευτική ζήτηση. Από την άλλη, σκοπός της προσομοίωσης είναι η εκτίμηση της αξιοπιστίας και της αποδοτικότητας αυτού του συστήματος ως προς την κάλυψη της ζήτησης ηλεκτρικής ενέργειας του νησιού σε βάθος χρόνου.

Έμφαση δίνεται αφενός στη διερεύνηση της λειτουργικότητας ενός τέτοιου συστήματος και τον προσδιορισμό της συμμετοχής των διαφόρων συνιστωσών του (ανεμογεννήτριες, υδροηλεκτρικοί σταθμοί, σύστημα αντλησιοταμίευσης) στην κάλυψη της ζήτησης και στην προσομοίωση του χρηματιστηρίου ενέργειας σε μη διασυνδεδεμένα νησιά.

Ως πρωτογενή δεδομένα εισόδου ελήφθησαν ωριαία ανεμολογικά δεδομένα του νησιού μήκους επτά ετών και δεδομένα βροχοπτώσεων, τα οποία μετατράπηκαν σε εισροές στον ταμιευτήρα, μέσω εννοιολογικού υδρολογικού μοντέλου. Ωστόσο, στις προσομοιώσεις χρησιμοποιήθηκαν συνθετικά δεδομένα ωριαίας ταχύτητας ανέμου και ημερήσιας βροχόπτωσης μήκους 1.000 ετών, τα οποία διατηρούν τα στατιστικά χαρακτηριστικά των παρατηρημένων χρονοσειρών.

Στόχος της προσομοίωσης του χρηματιστηρίου ενέργειας ήταν η εξαγωγή πορισμάτων που αφορούν τη βέλτιστη πολιτική διαχείρισης της ενέργειας στο μη διασυνδεδεμένο δίκτυο, μέσω της σύγκρισης του υπάρχοντος νομοθετικού πλαισίου με ένα πιο φιλελεύθερο διαχειριστικό μοντέλο.

Για να επιτευχθεί αυτό, αναπτύχθηκε μοντέλο πρόβλεψης της ταχύτητας του ανέμου σε χρονικό εύρος από 12 έως 36 ώρες έπειτα από δεδομένη χρονική στιγμή (ώρα). Το προαναφερθέν μοντέλο είναι απαραίτητο, καθώς η δημοπράτηση του συνόλου της παραγωγής ενέργειας κάθε ημέρας διεξάγεται στις 12 το μεσημέρι της προηγούμενης. Συνεπώς, εύκολα καταλαβαίνει κανείς ότι για την ορθολογική κατάθεση προσφορών είναι απαραίτητη η -έστω προσεγγιστική- πρόβλεψη της ταχύτητας του ανέμου για τις επόμενες 36 ώρες.

Στο χρηματιστήριο καταθέτουν προσφορές οι τρεις ενεργειακοί παίκτες του νησιού:

- Ο ιδιοκτήτης του αιολικού πάρκου, ως ο πλέον ανταγωνιστικός όλων, λόγω των μηδαμινών εξόδων λειτουργίας σε συνδυασμό με το πλούσιο αιολικό δυναμικό του νησιού;
- Ο ιδιοκτήτης του υδροηλεκτρικού έργου, ο οποίος έχει τη δυνατότητα ταυτόχρονης παραγωγής και αποθήκευσης ενέργειας;
- Ο ιδιοκτήτης του σταθμού πετρελαίου, ο οποίος, εξαιτίας των αυξημένων εξόδων μεταφοράς και περιβαλλοντικών φόρων, καταθέτει τις υψηλότερες προσφορές και καλύπτει τη ζήτηση όταν οι τεχνικοί περιορισμοί απαγορεύουν την είσοδο των άλλων δύο παικτών.

Τέλος, σημαντικό αντικείμενο μελέτης της εργασίας αποτελεί ο καθορισμός και η βελτιστοποίηση των κριτηρίων με τα οποία εν τέλει διαμορφώνεται η προσφορά των τριών ενεργειακών παικτών σε κάθε χρονική στιγμή.

Αναλυτικότερα, οι ερευνητικοί στόχοι που τέθηκαν στην υπόψη μελέτη, και μπορούν να γενικευτούν για μικρές μη διασυνδεδεμένες κοινότητες, είναι:

- Μελέτη του τρόπου αντιμετώπισης της στοχαστικής συμπεριφοράς των ΑΠΕ;
- Καθορισμός του επιπέδου εκμετάλλευσης των ΑΠΕ, με και χωρίς δυνατότητα αποθήκευσης των ενεργειακών πλεονασμάτων;
- Βελτιστοποίηση της χωρητικότητας των ταμιευτήρων και λιμνοδεξαμενών και της παροχετευτικότητας των αγωγών;
- Ελαχιστοποίηση του ρίσκου ενεργειακών ελλειμμάτων, χωρίς να αναιρείται η προτεραιότητα των αρδευτικών αναγκών του νησιού;
- Καθορισμός και βελτιστοποίηση των κανόνων λειτουργίας του συστήματος με σκοπό την επίτευξη υψηλής αξιοπιστίας τόσο στην άρδευση όσο και στην παραγωγή ενέργειας;
- Μείωση της τιμής της προσφερόμενης ενέργειας;
- Αντιμετώπιση του μονοπωλιακού χαρακτήρα της παραγωγής ενέργειας από τον υπάρχον πετρελαϊκό σταθμό;
- Προσομοίωση ενός χρηματιστηρίου ενέργειας τριών παικτών, με βάση εναλλακτικούς κανόνες λειτουργίας του;
- Καθορισμός και βελτιστοποίηση των κριτηρίων με τα οποία διαμορφώνεται η προσφορά των τριών ενεργειακών παικτών σε κάθε χρονική στιγμή;
- Παραγωγή συνθετικών χρονοσειρών ωριαίας ταχύτητας ανέμου;
- Διαμόρφωση κατάλληλου μοντέλου πρόβλεψης της ταχύτητας του ανέμου έως και 36 ωρών μπροστά;
- Βελτιστοποίηση του χρηματιστηρίου ενέργειας με στόχο την επίτευξη κέρδους από τους τρεις αντισυμβαλλόμενους με ταυτόχρονη μείωση της Οριακής Τιμής Συστήματος;
- Εξαγωγή γενικότερων συμπερασμάτων σχετικά με τη λειτουργία των ΥΒΕ, την προσφορά ενέργειας αυτών και την κατάρτιση χρηματιστηρίου ενέργειας σε μη διασυνδεδεμένα νησιά;
- Σύγκριση του υπάρχοντος μοντέλου «εγγυημένης τιμής» των ΑΠΕ με ένα πιο φιλελεύθερο διαχειριστικό μοντέλο.

Πρώτα απ’ όλα, στην παρούσα εργασία ερευνήσαμε τη λειτουργικότητα ενός τέτοιου έργου για να προσδιορίσουμε τα χαρακτηριστικά του υβριδικού ενεργειακού συστήματος για να ικανοποιήσουμε τις συνδυασμένες απαιτήσεις άρδευσης και παραγωγής ενέργειας. Επιπλέον, εξετάστηκε η ευαισθησία του υβριδικού ενεργειακού συστήματος στις συνιστώσες του σε μια προσπάθεια προσδιορισμού της βέλτιστης λειτουργίας του.

Δεύτερον, μέσω της προσομοίωσης του χρηματιστηρίου ενέργειας, εξαγάγαμε σημαντικά συμπεράσματα σχετικά με τη δυνατότητα δημιουργίας της βέλτιστης πολιτικής διαχείρισης ενέργειας σε ένα μη διασυνδεδεμένο δίκτυο, συγκρίνοντας το υφιστάμενο νομοθετικό πλαίσιο με ένα πιο φιλελεύθερο μοντέλο διαχείρισης. Συγκεκριμένα, το υφιστάμενο μοντέλο τιμολόγησης «εγγυημένης τιμής» συγκρίθηκε με μια μελέτη περιπτώσεων λειτουργίας χρηματιστηρίου ενέργειας στο νησί. Με αυτόν τον τρόπο, αξιολογήσαμε τα κίνητρα για επενδύσεις σε μονάδες ΑΠΕ και τη δυνατότητα μείωσης της τιμής της παρεχόμενης ηλεκτρικής ενέργειας.

Με την προσομοίωση του υβριδικού ενεργειακού συστήματος και του χρηματιστηρίου ενέργειας, εν τέλει επιτεύχθηκαν οι ακόλουθοι ερευνητικοί στόχοι:

- Υψηλή εκμετάλλευση της παραγωγής ανανεώσιμης ενέργειας λόγω της ευελιξίας που προσφέρει το υβριδικό σύστημα (αποθήκευση πλεονάζουσας ενέργειας), που επιτρέπει τη ρύθμιση της στοχαστικής συμπεριφοράς των μετεωρολογικών διεργασιών;
- Παραγωγή συνθετικών χρονοσειρών ανέμου;
- Διαμόρφωση κατάλληλου μοντέλου πρόβλεψης ανέμου έως και 36 ώρες μπροστά;
- Σύγκριση διαφορετικών προσομοιώσεων και προσδιορισμός των βέλτιστων κανόνων που διέπουν το υβριδικό ενεργειακό σύστημα σε μια προσπάθεια μεγιστοποίησης της αξιοπιστίας της παραγωγής ενέργειας και άρδευσης και ελαχιστοποίηση του μέσου κόστους ηλεκτρικής ενέργειας;
- Σύγκριση διαφορετικών προσομοιώσεων της αγοράς ενέργειας και καθορισμός των βέλτιστων κανόνων και σταθερών τιμών σε μια προσπάθεια ελαχιστοποίησης του κόστους ηλεκτρικής ενέργειας στο μη διασυνδεδεμένο νησί, αλλά και στην παροχή κινήτρων για επενδύσεις;
- Σύγκριση του υφιστάμενου μοντέλου "εγγυημένης τιμής" ΑΠΕ με τη λειτουργία χρηματιστηρίου ενέργειας.

Ακόμη, καταλήξαμε στα παρακάτω πορίσματα σχετικά με τη δομή ενός υβριδικού συστήματος ενέργειας σε μη διασυνδεδεμένο νησί και τη λειτουργία χρηματιστηρίου ενέργειας σε αυτό:

- Καθορισμός του επιπέδου εκμετάλλευσης των ΑΠΕ σε μικρές μη διασυνδεδεμένες κοινότητες και εξεύρεση λύσεων για μεγαλύτερη διείσδυση των ΑΠΕ στο νησιωτικό ενεργειακό σύστημα;
- Εξάλειψη των κινδύνων ενεργειακών ελλειμμάτων, εξασφαλίζοντας ταυτόχρονα την παραγωγή ενέργειας σε χαμηλότερες τιμές από σήμερα (μονοπώλιο σταθμών ντίζελ);
- Δυνατότητα ικανοποίησης της ζήτησης άρδευσης με υψηλή αξιοπιστία;
- Περιγραφή της λειτουργίας του υβριδικού ενεργειακού συστήματος;
- Περιγραφή της λειτουργίας της αγοράς ενέργειας;
- Προσδιορισμός της διάρθρωσης της αγοράς ενέργειας σε μη διασυνδεδεμένο νησί;
- Προσδιορισμός του βέλτιστου μοντέλου διαχείρισης πλεονασμάτων μέσω της λειτουργίας της αγοράς ενέργειας σε μη διασυνδεδεμένο δίκτυο;

- Αντιμετώπιση της δυνατότητας των παραγωγών ενέργειας να σχηματίσουν καρτέλ.

Παράλληλα, όσον αφορά τη λειτουργία του υβριδικού ενεργειακού συστήματος της Ικαρίας και της ενεργειακής της αγοράς, τα συμπεράσματα είναι τα εξής:

- Μείωση των εκπεμπόμενων ρύπων κατά 13.800 τόνους ετησίως;
- Κατανόηση ότι οι εποχιακοί περιορισμοί του υβριδικού ενεργειακού συστήματος βελτιώνουν όχι μόνο την κάλυψη της άρδευσης αλλά και την αξιοπιστία της παραγωγής ενέργειας;
- Καθορισμός της μέσης τιμής ενέργειας της Ικαρίας με βάση το υπάρχον μοντέλο τιμολόγησης;
- Παρουσίαση της δυνατότητας βελτιστοποίησης του υβριδικού ενεργειακού συστήματος και της ευαισθησίας του στα βασικά του χαρακτηριστικά, δηλαδή τη μέγιστη αποθηκευτική ικανότητα ταμιευτήρα και δεξαμενών, την ονομαστική ισχύ του σταθμού άντλησης και την ελάχιστη παροχή υδροστροβίλου;
- Διερεύνηση της δυνατότητας μείωσης της τιμής της ενέργειας που προσφέρεται στο μη διασυνδεδεμένο νησί;
- Αντιμετώπιση του μονοπωλιακού καθεστώτος παραγωγής ενέργειας από τον υπάρχοντα σταθμό πετρελαίου;
- Προσομοίωση ενός ενεργειακού χρηματιστηρίου τριών παικτών, διατηρώντας τους σχετικούς κανόνες λειτουργίας και προσδιορίζοντας τα κριτήρια της διαμόρφωσης της προσφοράς κάθε παίκτη;
- Βελτιστοποίηση των σταθερών τιμών της αγοράς ενέργειας σε μια προσπάθεια επίτευξης λογικών κερδών για όλους τους αντισυμβαλλομένους, μειώνοντας παράλληλα τη μέση τιμή της ηλεκτρικής ενέργειας;
- Σύγκριση του υφιστάμενου μοντέλου τιμολόγησης «εγγυημένης τιμής» για το υβριδικό ενεργειακό σύστημα της Ικαρίας όπως καθορίζεται από τη ΔΕΗ ΑΕ, το υφιστάμενο σύστημα οριακών τιμών για τη λειτουργία της αγοράς ενέργειας και ένα μοντέλο τιμολόγησης βασισμένο στη διακριτοποίηση;
- Προσδιορισμός της βέλτιστης λειτουργίας της αγοράς ενέργειας, η οποία έχει ως αποτέλεσμα χαμηλότερη τιμή ενέργειας κατά 36,6% σε σχέση με το υπάρχον μοντέλο και ταυτόχρονα δίνει τη δυνατότητα απόσβεσης των επενδύσεων των ενεργειακών παικτών.

Πρόδρομα αποτελέσματα της έρευνας παρουσιάστηκαν στο διεθνές συνέδριο της Ευρωπαϊκής Ένωσης Γεωεπιστημών (Mavritsakis *et al.*, 2019).

TABLE OF CONTENTS

Ευχαριστίες / [Acknowledgements] i

Abstract iv

Εκτενής Περίληψη / [Extended Abstract in Greek] v

Table of Figures xv

Table of Tables xvi

Table of Graphs xvii

Chapter 1: Introduction ..... - 1 -

- General Context ..... - 1 -
- Research Objectives ..... - 4 -
- Work Structure ..... - 5 -

Chapter 2: Bibliographic Overview of Hybrid Energy Systems ..... - 7 -

- About Hybrid Energy Systems ..... - 7 -
- Hybrid Wind and Hydraulic Energy Systems ..... - 11 -
  - Wind power ..... - 11 -
  - Hydropower ..... - 14 -
  - Hydro Pumped Storage ..... - 18 -
  - Wind Energy System with pumped storage ..... - 20 -
  - Examples of Hybrid Energy Systems around the world ..... - 23 -
- Existing Legal Framework of Hybrid Power Stations ..... - 29 -
  - Definition of Hybrid Power Stations ..... - 29 -
  - Hybrid Energy Systems in non-Interconnected Islands ..... - 30 -
  - Electrical Energy Pricing of Hybrid Systems ..... - 31 -
- Non-Interconnected Islands ..... - 32 -
  - About Non-Interconnected Islands ..... - 32 -
  - Non-Interconnected Islands Code ..... - 32 -

Chapter 3: Study Area ..... - 36 -

- General Context about Ikaria ..... - 36 -
- About the Hybrid Energy System ..... - 38 -
- Pezi Dam and Water Tanks ..... - 39 -
- Agios Kirikos Power Station ..... - 41 -
- Wind Parks ..... - 42 -
- Kato Proespera Pumping Station ..... - 43 -

Chapter 4: Input Data ..... - 45 -

- Reservoir inflow data ..... - 45 -

Wind Data .... - 48 -
  Historical Data .... - 48 -
  Energy Generation .... - 49 -
  Synthetic Data .... - 50 -
Energy Demand Data .... - 53 -
Irrigation Demand Data .... - 54 -
Chapter 5: Simulation Model .... - 55 -
Fixed design characteristics .... - 55 -
Hybrid Energy System’s operation .... - 58 -
Simulation of different operation models .... - 67 -
  Simulation No.1 .... - 68 -
  Simulation No.2 .... - 71 -
  Simulation No.3 .... - 73 -
  Simulation No.4 .... - 75 -
Comparison and conclusions .... - 77 -
Chapter 6: Optimization .... - 79 -
Single-variable optimization .... - 79 -
  Tank storage capacity .... - 79 -
  Pump station nominal power .... - 81 -
  Reservoir storage capacity .... - 81 -
  Minimum Pelton discharge .... - 83 -
  Aggregated results .... - 83 -
Multicriteria optimization .... - 85 -
Chapter 7: Energy Market .... - 87 -
About the operation of the Energy Market .... - 87 -
  Wind speed forecasting .... - 88 -
  Pricing model .... - 91 -
  Surplus management .... - 93 -
  Turbulent character of wind energy .... - 94 -
  Energy market structure .... - 95 -
Energy Market’s operation .... - 96 -
Simulation of different management models .... - 106 -
  Simulation No.1 .... - 106 -
  Simulation No.2 .... - 108 -
  Simulation No.3 .... - 110 -
  Simulation No.4 .... - 111 -

    - Simulation No.5 ..... - 113 -
  - Comparison and conclusions ..... - 115 -
- Chapter 8: Conclusions and future research perspectives ..... - 117 -
  - Conclusions ..... - 117 -
  - Future Research Perspectives ..... - 119 -
- References ..... - 120 -

TABLE OF FIGURES

Figure 1: Schematic layout of the simulation model of Ikaria's HES .... - 1 -
Figure 2: Wind potential and its exploitation at a global level .... - 11 -
Figure 3: Composition of typical wind turbine (El-Shimy, 2010) .... - 12 -
Figure 4: Spatial distribution of wind potential of Greece, in terms of mean annual wind speed (CRES) .... - 13 -
Figure 5: Installed hydropower capacity by country .... - 15 -
Figure 6: Operation of typical hydro turbine .... - 16 -
Figure 7: Typical components of water turbines .... - 17 -
Figure 8: Typical layout of Pelton (left) and Francis (right) hydro-turbines .... - 18 -
Figure 9: Operation of hydro pumped storage station (US Department of Energy) ..... - 19 -
Figure 10: Hybrid Energy System with pumped storage (Tao Ma, 2014) .... - 21 -
Figure 11: Operation of double piping pumped storage system (Ibrahim and Ilinca, 2012) .... - 22 -
Figure 12: El Hierro Island .... - 23 -
Figure 13: Upper reservoir of the pumped storage system .... - 24 -
Figure 14: Samso Island .... - 25 -
Figure 15: Kythnos Island .... - 26 -
Figure 16: Operation of Kythnos Hybrid Energy System .... - 27 -
Figure 17: Norway .... - 28 -
Figure 18: Cross-border transmission lines in south Norway (Statnett, 2011) .... - 29 -
Figure 19: Location of Ikaria island .... - 36 -
Figure 20: Ikaria Island .... - 37 -
Figure 21: Wind potential of Ikaria .... - 38 -
Figure 22: General view of Pezi dam .... - 40 -
Figure 23: Pezi dam (source: PPC SA) .... - 40 -
Figure 24: Ano Proespera Tank .... - 41 -
Figure 25: Kato Proespera Tank .... - 41 -
Figure 26: Stravokoundoura Wind Park .... - 43 -
Figure 27: Enercon E-44/900 Power Curve .... - 43 -
Figure 28: Top view and section of the pump station .... - 44 -
Figure 29: Pumping station's interior .... - 44 -
Figure 30: Operation of the hydrological model .... - 47 -
Figure 31: location Of HPS and other power stations' (Papaefthymiou, 2012) .... - 55 -
Figure 32: Highlight during water pumping into the Ano Proespera tank .... - 65 -
Figure 33: Determination of Limit Price (source: Oeko Institute) .... - 92 -

TABLE OF TABLES

Table 1: Energy pricing of Hybrid Systems (source: RAE) .... - 31 -
Table 2: RES energy generation on non-Interconnected islands (September 2016) ... - 35 -
Table 3: Installed units in the Autonomous Power Station of Ikaria .... - 42 -
Table 4: Aggregated results of different simulations .... - 77 -
Table 5: Aggregated results of different energy market simulations .... - 115 -

TABLE OF GRAPHS

Graph 1: Changes over time in electricity generation (BP statistical review, 2018)......- 7 -
Graph 2: Distribution of generation of 98W/P on non-interconnected islands ....- 34 -
Graph 3: Distribution of generation from 1.758 PV stations on non-interconnected islands.......- 34 -
Graph 4: Comparison of simulated vs. observed runoff ....- 48 -
Graph 5: Wind speed simulation for 10.000 hours.......- 49 -
Graph 6: Simulation of wind park operation ....- 50 -
Graph 7: Statistical characteristics of the sample of wind speed for December and August.......- 52 -
Graph 8: Energy Demand simulation for 10.000 hours.......- 53 -
Graph 9: Irrigation Demand simulation for one year ....- 54 -
Graph 10: Energy simulation from reservoir spill simulated for 50.000 hours ....- 59 -
Graph 11: Energy generation simulation for 10.000 hours ....- 60 -
Graph 12: Simulation of Surpluses and Deficits for 100.000 hours ....- 61 -
Graph 13: Simulation of energy generation of wind park and hydro power plants for 100.000 hours.......- 62 -
Graph 14: Simulation of generated and saved energy of the hydro pumped storage system for 30.000 hours ....- 64 -
Graph 15: Time series of storage completeness for a simulation of 300.000 hours..- 66 -
Graph 16: Time series of storage completeness for Simulation No.1 ....- 70 -
Graph 17: Energy generation mixture for Simulation No.1.......- 70 -
Graph 18: Course of storage completeness for Simulation No.2.......- 72 -
Graph 19: Energy generation mixture for Simulation No.2.......- 72 -
Graph 20: Course of storage completeness for simulation No.3.......- 74 -
Graph 21: Energy generation mixture for simulation No.3 ....- 74 -
Graph 22: Course of storage completeness for simulation No.4.......- 76 -
Graph 23: Energy generation mixture for Simulation No.4.......- 76 -
Graph 24: Irrigation and energy generation Reliability vS. tank storage capacity.......- 80 -
Graph 25: Mean power price per MWh for different tank storage capacities...............- 80 -
Graph 26: Irrigation and energy generation reliability VS. pumping station power .....- 81 -
Graph 27: Irrigation and energy generation reliability VS. reservoir capacity...............- 82 -
Graph 28: Mean power price VS. reservoir capacity.......- 82 -
Graph 29: irrigation and energy generation reliability VS. minimum turbine flow.......- 83 -
Graph 30: Sensitivity of energy generation reliability ....- 84 -
Graph 31: Sensitivity of irrigation reliability ....- 84 -
Graph 32: Time series of completeness of the reservoir and the tanks for the optimal HES simulation ....- 86 -
Graph 33: Ten forecast sets of wind speed for 36 hours lead time.......- 89 -
Graph 34: Average Forecast and observed energy generation refering to Graph 24 ..- 89 -
Graph 35: Two forecast sets of wind speed for 36 hours lead time.......- 90 -
Graph 36: Forecasted and observed energy generation refering to Graph 26 ....- 90 -
Graph 37: Decisions regarding the first energy LEVEL for 5.000 hours.......- 99 -
Graph 38: Simulation of deficits and surpluses BY the Wind Park for 30.000 hours - 100 -
Graph 39: Time series of energy generation and surpluses BY the APS for 30.000 hours - 102 -

Graph 40: Time series of completeness of the reservoir, the tanks and the power price for 100.000 hours - 104 -
Graph 41: Time series of energy surpluses BY the wind park and the autonomous power station for 30.000 hours - 105 -
Graph 42: Time series of completeness of the reservoir and the tanks for simulation No.1 - 107 -
Graph 43: Time series of completeness of the reservoir and the tanks for simulation No.2 - 109 -
Graph 44: Time series of power price for simulation No.2 - 109 -
Graph 45: Time series of completeness of the reservoir and the two tanks for simulation No.3 - 110 -
Graph 46: Time series of power price for simulation No.3 - 111 -
Graph 47: Time series of completeness of the reservoir and the tanks for simulation No.4 - 112 -
Graph 48: Time series of power price for simulation No.4 - 113 -
Graph 49: Time series of completeness of the reservoir and the tanks for simulation No.5 - 114 -
Graph 50: Time series of power price for simulation No.5 - 114 -

CHAPTER 1: INTRODUCTION

GENERAL CONTEXT

The aim of this thesis is to simulate and optimize the operation of the Hybrid Energy System (HES) of the non-interconnected island of Ikaria, and then to represent a hypothetical energy market to meet the electric energy demand of the island. A conceptual layout of this system is presented in Figure 1.

The construction of the project has begun since 2008 and has been just completed (June 2019). This project is part of the effort to meet the targets set by the so-called Kyoto Protocol for the production of energy. In particular, in 1997 a Protocol was adopted, which introduced legally binding emission reduction targets for the developed countries. The second commitment period of the Protocol started on 1 January 2013 and ends in 2020. It involves 38 developed countries, including the EU and its 28 Member States.

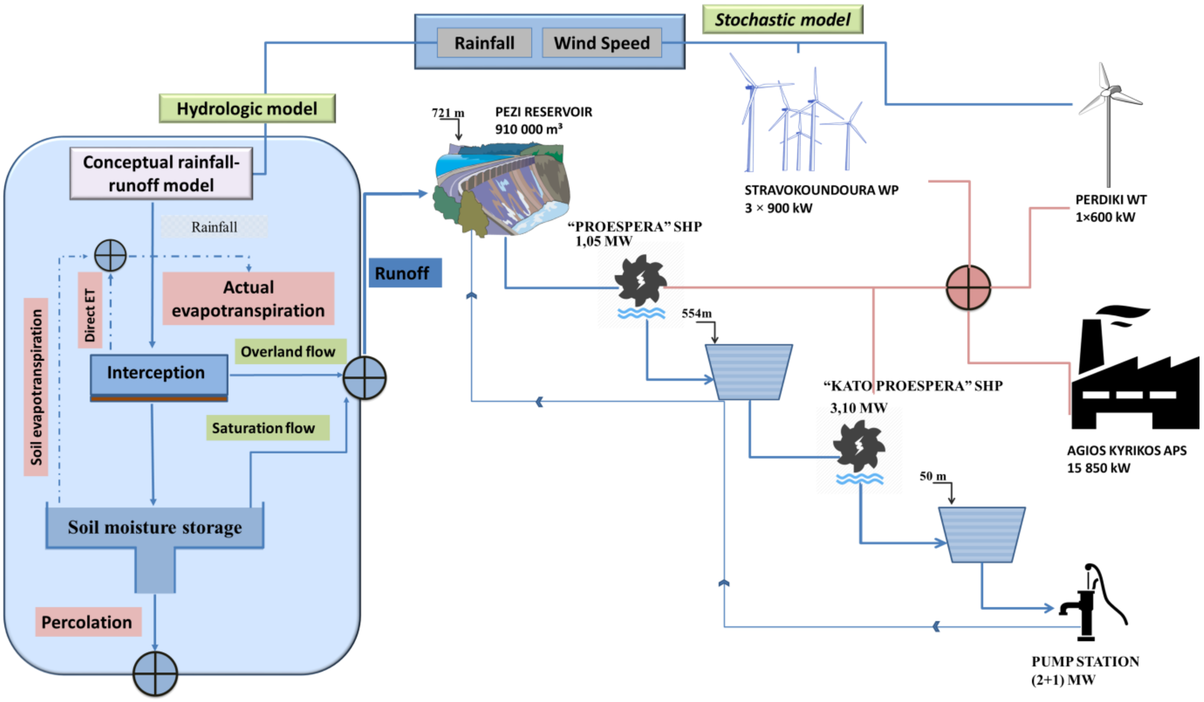


FIGURE 1: SCHEMATIC LAYOUT OF THE SIMULATION MODEL OF IKARIA'S HES

The European Council adopted an integrated approach in terms of climate and energy policy, aimed at combating climate change and increasing the EU's energy security, while enhancing its competitiveness and transforming it into a highly energy-efficient economy with low carbon emissions. The requirements adopted by Heads of State and Government concerned:

- Reduction of greenhouse gas emissions by at least 20% below 1990 levels;
- 20% of EU energy consumption from renewable sources;
- 20% reduction in primary energy use compared to projected levels through improved energy efficiency.

The above requirements are known as 20-20-20 targets.

Particularly in island areas, and especially in the non-interconnected ones, which are served by autonomous power stations, the penetration of installations of various forms of Renewable Energy Sources (RES), such as wind, photovoltaic, biomass, and hydroelectric plants, can cover a significant part of the supply needs of their electricity system, also reducing the environmental impacts of fossil fuel systems. Given the high operating costs of conventional production units in the remote islands, due to rising transport costs and environmental taxes, RES penetration is all the more necessary.

Nevertheless, the levels of RES penetration in the Greek islands (particularly wind and solar) are still low, despite their high potential, due to the various shortcomings of such power generation facilities. The stochastic nature of the power produced by photovoltaic and wind turbine installations and their limited ability to control their power make it doubtful that the operation and performance of such facilities in remote areas is reliable. RES dependence on natural phenomena has the effect of varying their energy potential in time. However, through appropriate design, as well as by combining them with other forms of energy, in order to store the power excesses, it is possible to achieve a high degree of coverage of electricity demand in not interconnected areas.

As part of this effort, the implementation of Hybrid Energy Projects, such as that of Ikaria, has been initiated by the Public Power Corporation (PPC SA). As shown in Figure 1, the hybrid energy system of Ikaria includes a diesel generator (Agios Kyrikos Station), four wind turbines, three hydro-turbines and a pumping station. Its aim is to produce energy through the combination of two different forms of RES, i.e. wind and hydroelectric, by storing the excess wind energy through pumping. The Load Management System of the project, in addition to the two above-mentioned forms of RES, will also control the power of Agios Kyrikos Station, the island's consumption load, the water fluxes across the pumped-storage system (comprising an existing reservoirs at Pezi and two interconnected tanks), and the stability of the island's electricity network, in order to eventually keep the maximum possible coverage of the island's consumption by RES.

This project is one of the first in Europe, whose evolution of operation will provide a credible response to the very important issue of storage and controlled distribution of clean energy.

Key objective of this thesis is the development of a stochastic simulation model for the representation of this complex system, which allows understanding its operation and the collaboration of the various forms of energy involved in the production of the desired electricity, by setting the irrigation use in higher priority. Emphasis is, on the one hand, to investigate the functionality of such a project and to determine the sharing of the various power components of the system (conventional station, wind turbines, hydroelectric stations, pumps) to meet combined water and electricity demands across the non-interconnected island. The management of the hybrid system is expressed in terms of rules and limitations that have been set during the study to ensure the fulfillment of both irrigation and electric energy demands.

In the context of simulations, we used synthetic reservoir inflows and synthetic hourly wind data of 1.000 years length that retain the statistical characteristics of the observed time series. The overall purpose is to estimate the reliability and efficiency of this system to meet the island's demand for electricity over time. As raw input data for the generation of synthetic time series of hourly resolution, we used 10-min wind data for seven years and daily rainfall data for a 40-year period. The rainfall was used as input to a conceptual hydrological model, which has been calibrated against a short (2.5 years) sample of observed inflows.

Next, a (near real-time) energy stock simulation was developed to draw conclusions on the optimal energy management policy on the non-interconnected network, by comparing the existing legislative framework with a more liberal management model. More specifically, our aims is to compare the existing "guaranteed price" model of RES, in which the RES energy players do not bid on the energy market, with a free market case study in a non-interconnected island. In this way, conclusions are drawn regarding the incentives to invest in RES units and optimal management to reduce the price of the supplied electricity.

The following three energy players are bidding on the stock market:

- The owner of the wind park, being the most competitive of the three because of the low running costs and relatively high winds.
- The owner of the hydroelectric power plant, capable of producing and storing energy simultaneously.
- The owner of the oil station, who, due to increased transportation costs and environmental taxes, deposits the highest bids and meets demand when technical restrictions prohibit the entry of the other two players.

An important requirement of this work is to define and optimize the criteria by which the three energy players are bidding at all times. The wind park and the oil station owner will have almost constant prices, while the owner of the hydroelectric power plant can modify his offer depending in plethora of factors.

Key element of the energy stock simulation framework is the wind forecasting procedure, providing wind speed scenarios over 12 to 36 hours lead time after each certain time step. Such an approach is necessary as the auctioning of all overnight energy production takes place at 12 noon of the previous day. Therefore, it is easy to understand that for the rational submission of tenders it is necessary to predict the intensity of the wind for the next 36 hours, as more accurately as possible. In our analyses we developed two alternatives, i.e. an advanced approach based on a novel combination of stochastic models with analogues, and a simpler procedure, which retains the quite high accuracy of deterministic meteorological forecasts.

RESEARCH OBJECTIVES

This project is one of the first of its kind in Europe (pioneering case is the Spanish island of El Hierro), making it a first-class opportunity to control the issue of storage and controlled distribution of the produced energy. In addition, the energy stock market simulation is expected to generate significant energy policy outcomes in the non-interconnected network.

More specifically, the main research objectives that have been set are:

- Study of the degree of response to the stochastic behavior of RES in the non-interconnected network;
- Determination of the level of exploitation of RES in small non-interconnected communities, with or without the possibility of storing energy surpluses;
- Optimization of design quantities, i.e. reservoir, tank and pipeline capacities;
- Minimizing the risk of energy shortages, by keeping in higher priority the fulfilment of irrigation needs of the island;
- Definition and optimization of the system operating rules, in order to achieve the maximum irrigation and power generation reliability;
- Reduction of the price of energy offered;
- Addressing the monopoly status of energy production from the existing oil station;
- Finding solutions for greater RES penetration in the island energy system;
- Simulation of a three-player energy stock, by preserving the associated governing rules;
- Definition and optimization of the criteria for the three energy players' offerings at each time point;
- Production of synthetic wind time series both in long-term simulation and short-term forecasting mode;
- Configuring a suitable wind forecast prediction model up to 36 hours ahead;

- Optimization of the energy stock exchange with the aim of achieving profit by the three counterparties while reducing the Limit System Price;
- Deliver general conclusions on the operation of the HES, the energy supply and the development of an energy exchange on non-interconnected islands;
- Comparison of the existing "guaranteed price" model of RES with a more liberal management model.

Preliminary outcomes of this research have been presented in the General Assembly of the European Geosciences Union (Mavritsakis *et al.*, 2019).

WORK STRUCTURE

The thesis is divided into eight chapters. This **first chapter** introduces a preamble to the subject and the research objectives of the work.

The **second chapter** provides a brief bibliographic overview on the meaning and usefulness of hybrid plants and pumping and, at the same time, the presentation of the characteristics of the different types of energy that cooperate in such projects. Also, a review of hybrid energy projects built around the world is being done.

In **chapter three** an overview of the non-interconnected island network is made. Some general features of the island of Ikaria and the region of interest are given. In addition, data on the island's local production plant, Pezi dam, the two wind farms and the possibilities of system expansion are reported.

The **fourth chapter** introduces the system input data and their processing. More specifically, an explanation of the hydrological model for the transformation of catchment rainfall to reservoir inflow data is made. Next, the island's energy demand pattern and its synthetic wind turbine data are presented.

The **fifth chapter** explains the simulation model of the hybrid energy system and presents all associated rules and assumptions. Initially, all technical characteristics that govern the system are specified, qualitatively and quantitatively. The results of the model are then known regarding the island's irrigation and power reliability, and the operation of RES with and without the ability to store surpluses is compared.

In the **sixth chapter** we study the possibility of optimizing the system components (reservoir capacity, pipeline capacity, etc.) and their effect in terms of reliability and cost. In addition, we attempt to optimize its operating rules against financial as well as other criteria. Furthermore, conclusions are drawn regarding the possibility of improving the operation of the system, by means of economic criteria.

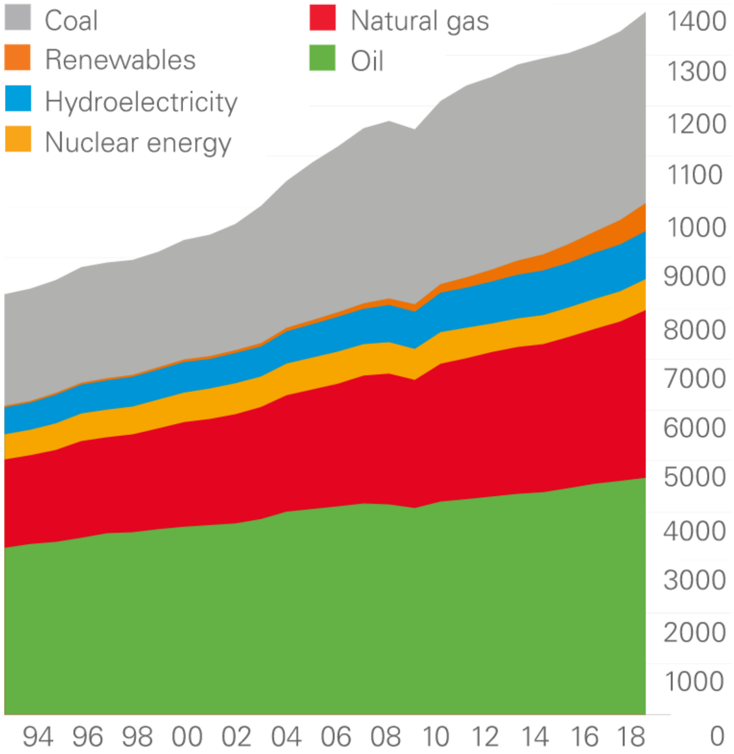
The **seventh chapter** presents the simulation of the energy stock exchange. To achieve this, we first analyze the stochastic wind forecasting model for the next day and then analyze the stock market procedure. Next we describe the real-time operation of the energy stock market, with the three players participating by bidding. An important task is to define the criteria by which the three energy players make their offers across the 24-hour lead time. At the end, different perspectives on the organization and operation of the stock exchange are compared, and then their results are presented.

The **eighth chapter** summarizes the conclusions and suggestions on the design and operation of hybrid energy systems on non-interconnected islands. These concern the optimization of the energy stock exchange with the aim of achieving profit from the three counterparties, while reducing the Limit System Price and assessing the existing "guaranteed price" model of RES.

CHAPTER 2: BIBLIOGRAPHIC OVERVIEW OF HYBRID ENERGY SYSTEMS

ABOUT HYBRID ENERGY SYSTEMS

Energy dependence on fossil fuels for electricity production, such as oil, coal and gas, raises technical issues, such as their expected exhaustion, and policy issues, related to their extraction and exploitation. In addition, combustion of fossil fuels is the main cause behind the disruption of ecological balance. These are the key factors that in recent decades RES has garnered interest within research and development studies. The main technology used for large-scale production and distribution of renewable electricity is hydropower (Graph 1).



GRAPH 1: CHANGES OVER TIME IN ELECTRICITY GENERATION (BP STATISTICAL REVIEW, 2018)

The stochastic nature of most forms of RES raises some technical and economic constraints in their use to meet energy needs. For example, solar energy requires the use of storage media due to fluctuations in its availability. The same applies to wind power and small-scale hydroelectric power plants. Nonetheless, there are other forms of RES that are more stable and predictable, such as geothermic and biomass. These have led to the research and development of hybrid power generating systems, which are generally defined as mixed systems where multiple sources of electricity generation technologies are combined. According to existing legal framework in Greece (Law N.3468 / 2006), hybrid is called any power system that uses at least one form of RES, the total energy absorbed by the Network does not exceed 30% of the total energy consumed to fill the storage system of this plant per year and the maximum power output of the RES station units may not exceed the installed capacity of the storage units of this plant plus 20%.

An electrical system is characterized by its production (supply) and the associated energy consumption (demand). Electricity has the characteristic that it cannot be stored in the large scale, thus the energy production must be in constant balance with demand (supply-demand balance). On the other hand, most of renewable energy sources are unable to meet this requirement, as they rely on unpredictable meteorological processes.

This problem appears more pronounced in small autonomous electrical systems, such as those of many Greek islands, where the power demand is strongly fluctuating both across seasons and within the 24-hour period. The lack of local industry that consumes significant energy at night as well as the steep increase in demand in the summer months due to tourism and the extensive use of air conditions, cause severe inequalities in the energy demand profile.

The disparity of demand, from the in-daily to the over-annual scales, coupled with the significant fluctuations of the energy produced by wind turbines, make their installation in a non-interconnected island inefficient and therefore economically unprofitable. For this reason, it is necessary to develop hybrid systems that employ a combination of different technologies, also comprising energy storage facilities. The parallel use of wind systems with internal combustion engines is a widespread applied technology.

Autonomous Hybrid Power Generation Systems are designed for the generation and management of electricity in remote areas. They are independent of the major national networks and integrate many different types of power sources, mainly consisting of RES. Their size in terms of power capacity can vary from many MW, for example, in isolated islands, up to a few kW, as in isolated holiday homes. Small hybrid systems of only a few kW of power capacity can be used in isolated areas for low power applications, such as telecoms transponders. Hybrid parks are the first step for a widespread use of renewable energy sources, as they combine wind, solar and hydro power with existing conventional power plants (gas or petroleum). In this way, renewable sources and traditional ones can complement each other, to provide economically effective and environment-friendly solutions.

Today, hybrid power systems in remote areas employ well-established technologies that make it possible to supply AC power at a defined frequency. The production of electrical power at our level of consumption relieves us of the cost of manufacturing the electricity transmission network and minimizes the power losses occurring on this network, which is particularly important for long-distance networks.

Power plants producing electricity from renewable energy sources operate not only when their energy can be directly absorbed by the grid but also outside of that time, for example to pump water. This aims to raise the water level to a reservoir from which electricity can be generated at peak load times to absorb it from the grid. In order to improve the effectiveness of these projects, they may also use additional electricity during base load hours either from the grid or from conventional sources, to store even more energy, thus further contributing during peak load times, when the energy price is higher.

The most suitable and economical way to store electricity (which is also strongly favorable for Greek islands) is via pumping, by means of reversible hydroelectric projects (Koutsoyiannis *et al.*, 2009). A typical scheme consists of a wind park, a hydro-turbine, a pumping station, and two tanks for water recycling. The two tanks must be in relatively close distance and have a large elevation difference. The wind farm produces electricity, which, as long as it cannot be directly absorbed by the non-interconnected electricity grid, is used to pump water from the bottom to the upper tank. Thus, electricity is transformed into hydrodynamic energy since water is stored in the upper tank. At peak demand time or when wind is not blowing and there is demand for electricity, the top tank water is used to operate the hydro turbine. The combined use of wind energy with pumped storage is a solution that can lead to a substantial increase in the coverage of RES needs in medium- or large-scale, islands, thus ensuring autonomy.

Other ways of exploiting energy excesses include batteries, compressed air energy storage and desalination:

- On its most elementary level, a battery is a device consisting of one or more electrochemical cells that convert stored chemical energy into electrical energy. Each cell contains a positive terminal, or cathode, and a negative terminal, or anode. Electrolytes allow ions to move between the electrodes and terminals, which allows current to flow out of the battery to perform work. Advances in technology and materials have greatly increased the reliability and output of modern battery systems, and economies of scale have dramatically reduced the associated cost. Continued innovation has created new technologies like electrochemical capacitors that can be charged and discharged simultaneously and instantly, and provide an almost unlimited operational lifespan.
- Compressed air energy storage (CAES) is a way to store energy generated at one time for use at another time. At utility scale, energy generated during periods of low energy demand (off-peak) can be released to meet

higher demand (peak load) periods. Since the 1870's, CAES systems have been deployed to provide effective, on-demand energy for cities and industries. While many smaller applications exist, the first utility-scale CAES system was put in place in the 1970's with over 290 MW nameplate capacity. CAES offers the potential for small-scale, on-site energy storage solutions as well as larger installations that can provide immense energy reserves for the grid (source: Energy Storage Association).

- In several islands, lack of accessible and safe water resources has resulted in the adoption of desalination technologies to produce potable water, which in the past was usually transported with tank vessels from the mainland. Often, these technologies are able to meet the entire water demand, yet by consuming large amounts of electricity. With an electrical consumption that ranges between 7-14 and 2-6 kWh/m^3 for thermal and membrane-based technologies, respectively, the entire desalination process might account for up to 30% of the total electrical load of a small island. Moreover, high electrical consumption, combined with a costly and inefficient electricity system, increase water production cost, which varies from 7 to 10 AC/m^3, about ten times that on the mainland.

Most Greek islands suffer from water scarcity. The above pumped energy storage system can be combined with desalination units that will use part of the wind power to produce potable water. This ensures the availability of water, not only for energy use, but also for producing drinking water. Thus, hybrid projects enable wider use of RES in networks with limited capacity to absorb energy from RES, such as non-interconnected islands.

Many Greek islands use in parallel wind and diesel to meet power demands. In such systems, wind turbines operate as a reserve and their use can deliver great fuel economy. The use of an energy storage system (e.g. battery, pump station, etc.) allows, as we will see in more detail below, the rapid coverage of possible loss of wind power before the system is unable to cover the loads (black out). There are different types of hybrid systems combining renewable energy technologies.

Examples of such applications are the combination of wind turbines with photovoltaic systems, or wind turbines and photovoltaic panels with desalination, while the parallel use of small hydropower works can increase the reliability of the system, due to their predictable operation and rapid response.

In case of hybrid systems, optimization is made in the context of planning and sizing of the units, as well as the long-term operation and real-time control of the system.

Given the stochastic nature of renewable energy production, the importance of storing surplus energy in non-interconnected parts of the electricity grid becomes encumbering. The variation in energy production outweighs that of demand, resulting in a drastic reduction in system reliability. The irregular fluctuations of power also cause major problem to the electricity grid, thus making essential to apply a means to destroy the surplus power.

HYBRID WIND AND HYDRAULIC ENERGY SYSTEMS

WIND POWER

The first use of wind energy was in navigation, while the first windmills were used for cereal grinding and water pumping. With the development of technology and the search for alternative energy sources for electricity production, the interest turned into the use of wind energy. The first windmill for power generation was built in 1888 in Cleveland, Ohio (USA), with a power of 12 kW, and today the global record is 9.5 MW (MHI Vestas V164-9.5MW). An overview of wind potential and its sharing at the global scale is given in Figure 3.

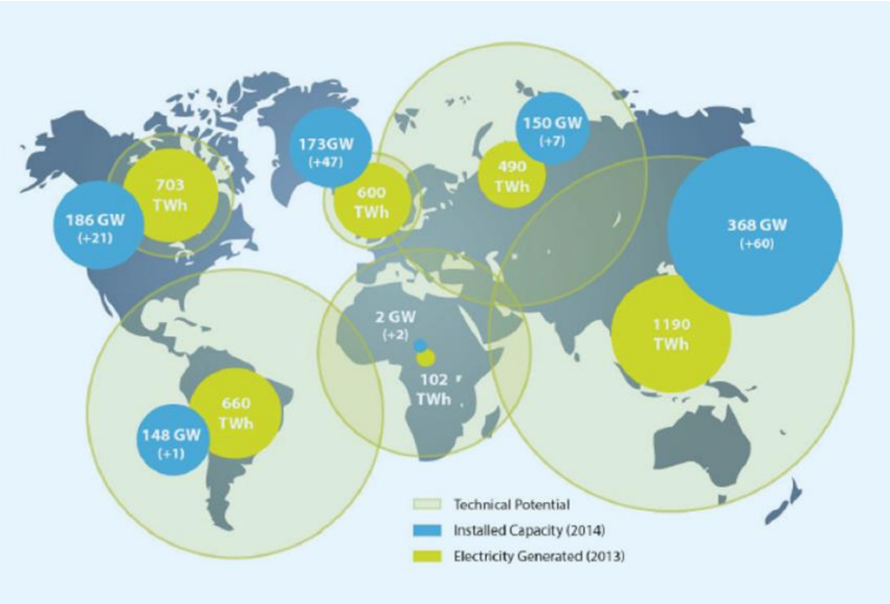


FIGURE 2: WIND POTENTIAL AND ITS EXPLOITATION AT A GLOBAL LEVEL

Wind energy is created indirectly by solar radiation, because uneven heating of the Earth's surface causes the movement of large masses of air from one region to another, thereby creating the winds. It is a mild form of energy, environmentally friendly, practically inexhaustible. If current technology was able to exploit the total wind potential of the Earth, it is estimated that the electricity produced at a certain period would be more than twice as high as humanity's needs in the same period (CRES, 1998). It is estimated that 25% of the surface of the Earth prevails winds at an average annual speed of more than 5.1 m/s at a height of 10 m above the ground.

Nowadays, the exploitation of wind energy is done almost exclusively with machines that convert wind energy into electricity and are called wind turbines. They are classified into two types:

- wind turbines with a horizontal axis, where the rotor is a propeller type and the shaft can rotate continuously parallel to the wind (Figure 2);
- wind turbines with a vertical axis that remains stationary.

In the global market, the horizontal axis wind turbines prevail at a rate of 90%. Their power exceeds 1 MW and can be connected directly to the country's power grid. So, a grid of many wind turbines, called a wind farm, can function as a power plant. Wind energy provided 14% of electricity in the European Union in 2018, from 12% in 2017, according to statistics released by the European Wind Energy Association. Wind power raised in Europe by 11.3 GW in 2018, 8.6 GW of land-based wind turbines and 2.65 GW of offshore wind farms.

When the winds blow at a speed higher than a certain value, then the wind potential of the site is considered exploitable and the required facilities can be made economically viable. Besides, the cost of manufacturing wind turbines has dropped considerably and wind power can be considered to be in the "first maturity period" as it is more competitive than conventional energy.

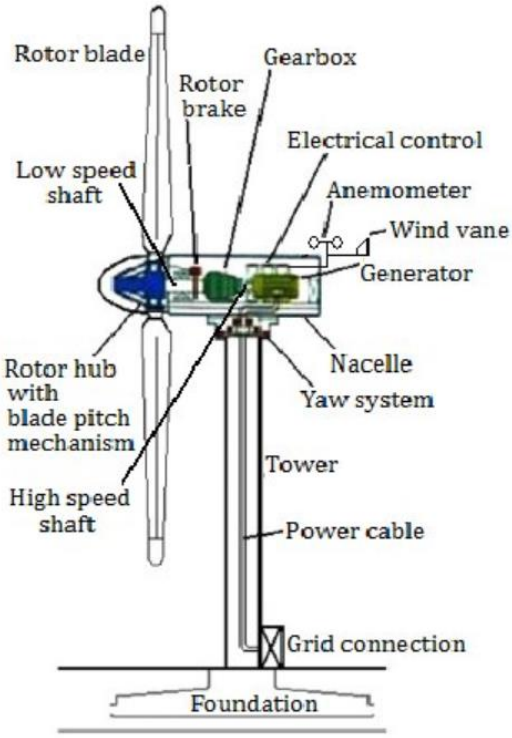


FIGURE 3: COMPOSITION OF TYPICAL WIND TURBINE (EL-SHIMY, 2010)

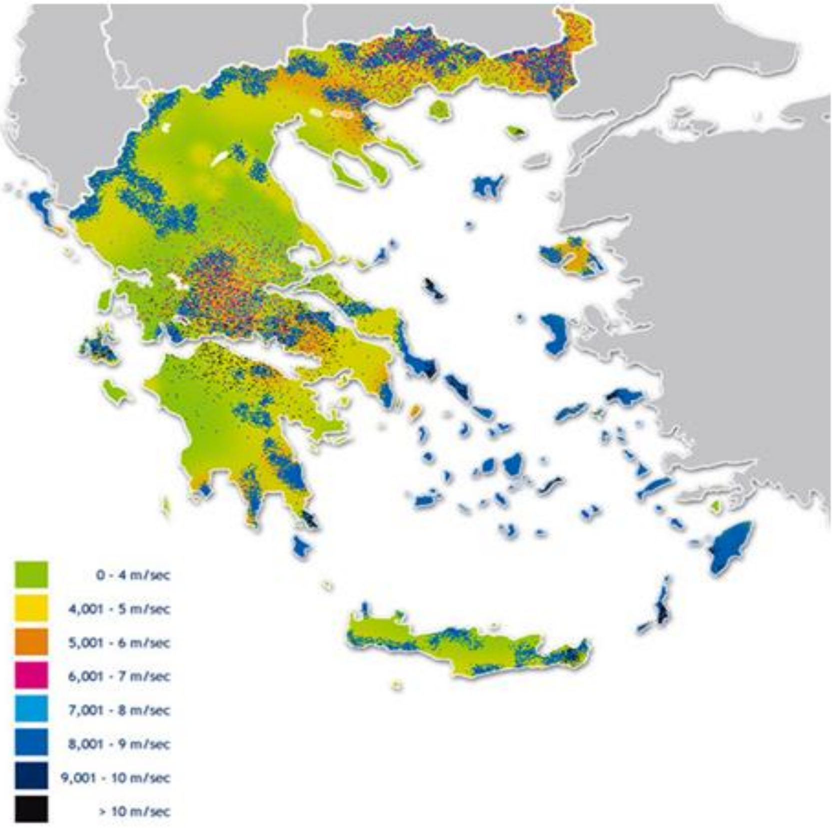


FIGURE 4: SPATIAL DISTRIBUTION OF WIND POTENTIAL OF GREECE, IN TERMS OF MEAN ANNUAL WIND SPEED (CRES)

As indicated in Figure 4, our country has a rich wind potential, and wind power can become an important lever for its development. As indicated in Figure 3, the wind power installed capacity in Greece is comparable to the rest of the world. Since 1982, when the first wind farm in Kythnos was installed by PPC, up to today, wind power plants with a total wind power of 203 MW have been built in Andros, Evvoia, Limnos, Lesvos, Chios, Samos and Crete. Particularly interesting is the private sector for the exploitation of wind energy, especially in Crete, where the Ministry of Development has issued rights for developing new wind farms of a total capacity of dozens of MW.

The systematic exploitation of the large wind potential of our country can offer many advantages:

- increasing electricity production, while saving significant quantities of conventional fuels, which entails exchange benefits;
- significant reduction of environmental pollution, since it has been calculated that the generation of electricity of a single 550 kW wind turbine at one year replaces the energy generated by the burning of 2,700 barrels of oil, in other

words preventing the emission of approximately 735 tons of CO_2 per year and 2 tons of other pollutants;

- the creation of many new jobs, since it is estimated that for each new MW of wind energy 14 new jobs are created.

Potential problems of wind power are noise from the operation of wind turbines, rare electromagnetic interference in radio, television and telecommunications (which are yet addressed by technological means) and possible aesthetic problems.

HYDROPOWER

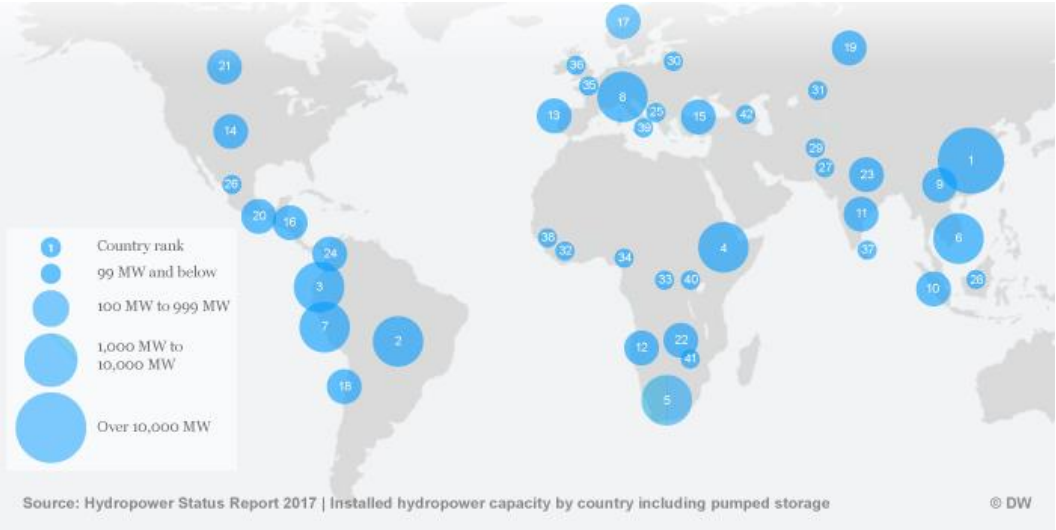
Since ancient Egyptian times, people have used energy in running water to operate machinery and grind grain and corn. However, hydropower has the greatest influence on people's lives during the 20th century than at any other time in history. Hydroelectric power has played an important role in the realization of the wonders of electricity and has helped to boost industrial development. Hydroelectric power continues to produce 24% of global electricity.

The first hydroelectric station was built in 1882 in Appleton, Wisconsin, and produced 12,5 kW, thus providing light to two papermakers and a house. Hydroelectric plants vary in size from several hundred kWs to several hundred MWs, but some hydropower plants have capacities of up to 10 GW and provide electricity to millions of people. At a global level, they have a capacity of 675 GW and produce more than 2,3 trillion kWh of electricity, equivalent to 3,6 billion barrels of oil.

Stored water in a high elevation has a dynamic energy that turns into kinetic energy when water flows to lower areas. With hydroelectric works it is possible to exploit the energy of water for the production of electricity that is supplied to the electricity grid. The conversion of water energy using hydraulic turbines produces hydropower. This energy is classified into large and small-scale hydroelectric power. Typically, small-scale hydropower plants differ in terms of power capacity, yet the key technical difference is the lack of storage capacity, which allows regulation of flows.

Large-scale hydropower plants require the construction of dams creating large reservoirs, with significant impacts on the riverine ecosystem and the surrounding environment. In contrast, small-scale systems are located next to rivers and canals, resulting in less environmental impacts. The fast-moving water is driven through a tunnel in order to operate the turbines, thus producing mechanical energy. A generator converts this energy into electricity. Contrary to what happens with fossil fuels, water is not disposed of in the production of electricity and can be used for other purposes.

Of course, large hydroelectric works can only be developed in areas with significant waterfalls, rich water resources and suitable geological configuration (Figure 5). Typically, the energy ultimately produced in this way is only used in conjunction with other conventional sources of energy at peak times. In Greece, hydropower covers about 10% of our energy needs.



Source: Hydropower Status Report 2017 | Installed hydropower capacity by country including pumped storage

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FIGURE 5: INSTALLED HYDROPOWER CAPACITY BY COUNTRY

The advantages of using hydraulic power are:

- The hydroelectric plants can be switched on as soon as extra electricity is requested, as opposed to the thermal stations (coal, oil), which require preparation time;
- It is a clean and renewable energy source, with obvious advantages (saving money, natural resources, environmental protection);
- Other water uses, such as water supply, irrigation, navigation, recreation, sports, ext., together with flood protection, are also available through the water reservoirs;
- It is practically an inexhaustible energy source and helps reduce dependence on conventional energy resources;
- It is a domestic source of energy and contributes to strengthening energy independence and security of energy supply at national level;
- It is geographically scattered and leads to the decentralization of the energy system, but also enables the rational use of local energy resources;
- It can be the core of revitalizing areas that are economically and socially degraded, as well as contributing to local development by promoting relevant investments;

- It does not produce atmospheric pollutants and noise (except for low intensity and time in the construction phase);
- The reservoir can lead to the creation of a wetland.

Negative impacts of the use of hydraulic power include the high cost of building dams and installing equipment, as well as the usually long time required to complete the project, the intense environmental alteration of the project area (including geomorphology, fauna and flora), as well as possible population movements, area degradation, land use changes required. In addition, changes in the microclimate, as well as an increase in their seismic risk, have been observed in large project sites.

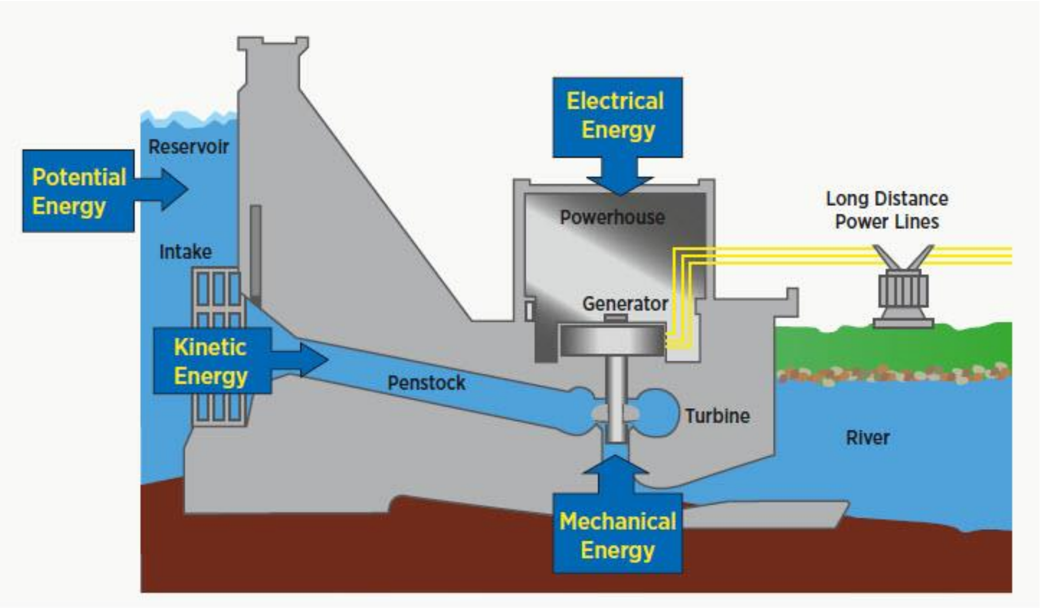


FIGURE 6: OPERATION OF TYPICAL HYDRO TURBINE

The operation of the hydroelectric units is based on the transformation of hydrodynamic energy (water stored at an upper elevation) to kinetic and pressure energy of moving water to a lower elevation, as shown in Figure 6. For this purpose, a barrier is formed that holds the required amount of water in the created reservoir. During its passage through the drop line it moves a turbine which turns the generator on.

The amount of electricity produced is mainly determined by the volume of flowing water and the elevation difference between the free surface of the reservoir and the turbine (referred to as head). The amount of electricity produced is proportional to these two sizes. Consequently, the electricity generated depends on the reservoir size, given that the larger is the capacity of the reservoir, the larger portion of inflows can be exploited. For this reason, only in areas with rich water resources, suitable geological characteristics and suitable geomorphological configuration can hydroelectric projects be productive. Typically, the energy ultimately produced is only used in addition to other conventional energy sources, covering peak loads.

A hydro turbine converts the dynamic energy of water into mechanical energy through continuous flow of fluid and constant rotary motion. Transforming the energy of the passing fluid under a constant supply to mechanical energy is done in the rotating part of the machine, which is called a rotor, by means of thrust. The drive torque is transferred to the rotor shaft, which is coupled to the electric generator shaft, which converts the mechanical power to electricity (Figure 7).

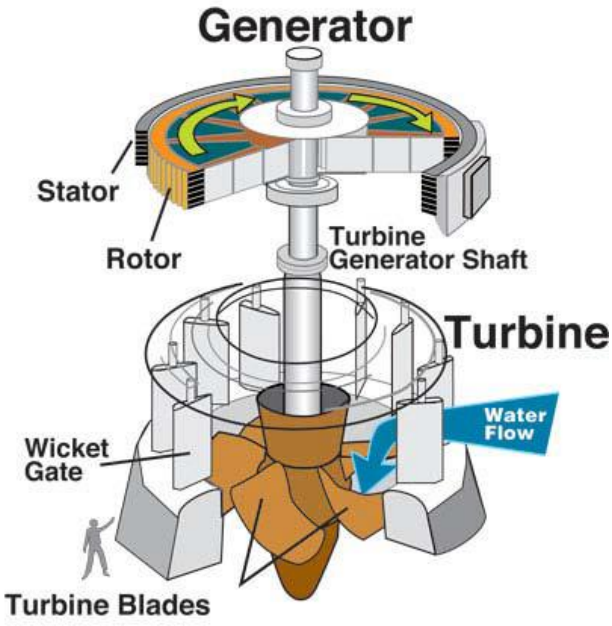


FIGURE 7: TYPICAL COMPONENTS OF WATER TURBINES

Modern hydro-turbines are divided into two categories:

- Action or partial infringement
- Reaction or total infringement

Their distinction is based on the fact that in part-stroke hydro turbines, only a part of the rotor contributes to the conversion of energy, while the total invasion is the opposite. Moreover, in the partial infringement turbines the runner operates in a space of uniform static pressure (zero degree of reaction), while in the total infringement turbines the flow through the rotor is made by a parallel change of the static pressure of the liquid.

Typical types of action turbines are Pelton type (Figure 8, left), which are used for medium and large dropping heads (H > 50 m), while the hydro switches include the Kaplan (axial flow) and Francis (radial and mixed flow) for small and medium heads, respectively.

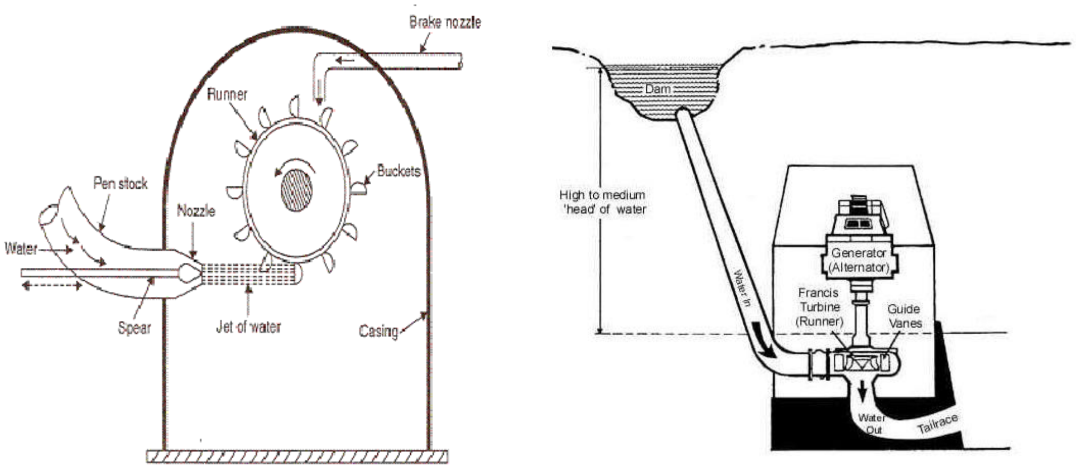


FIGURE 8: TYPICAL LAYOUT OF PELTON (left) AND FRANCIS (right) HYDRO-TURBINES

In the Pelton hydro turbine, at each time, only 2-3 runners of the rotor accept the beam of water and alternate in succession. The rotor is positioned over the free level of the lead duct to ensure smooth operation.

Unlike Pelton, the Francis cursor (Figure 8, right) consists of roller rotors that "absorb" the energy of water and turn the rotor shaft. The water falling from the rotor due to gravity is driven from the outlet section into the lead canal and then into the watercourse bed or in a tank, depending on the application.

HYDRO PUMPED STORAGE

The operation philosophy of the hydro pumped storage system is simple. Redundant energy supplies the pumps through which the working medium (water) rises through the pipes from the bottom reservoir to the upper, thus enabling us to store energy excess in the form of dynamic energy. When at another time we need energy, the water from the top tank is allowed to travel through the downhill pipelines to the bottom reservoir, passing through the hydro turbines generating the desired energy.

The dimensions of the two tanks are enough as to ensure that only a small percentage of the volume of the stored water is used and will be capable of converting the available energy into dynamic and vice versa, excluding the possibility of one of the two tanks being completely emptied.

It is concluded that pumped storage systems have double benefit (Figure 9):

- They absorb energy excess during low demand hours by converting it to dynamic energy stored in the upper reservoir;
- They provide to the network at peak hours the energy they have saved, and in most cases also generate primary energy from the use of natural inputs in the upper reservoir.

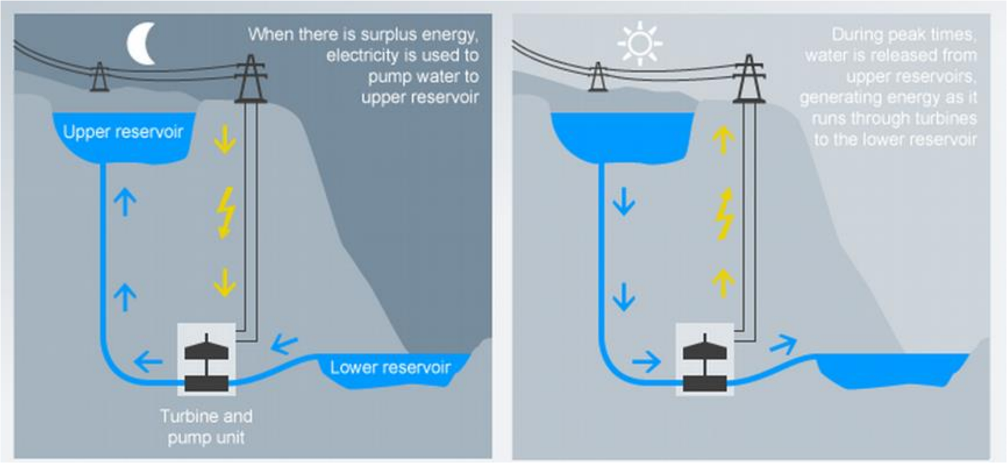


FIGURE 9: OPERATION OF HYDRO PUMPED STORAGE STATION (US DEPARTMENT OF ENERGY)

Switching their operation between pumping and power generation can happen several times a day or once a week. Of course, the last two switching operations require a storage tank of very large capacity.

It is obvious that this process of converting electricity to hydraulic (pumping) energy and then re-turning it into electricity (hydro turbine operation) is accompanied by energy losses. Total energy losses in a pumped-power cycle in a medium-sized hydroelectric project reach about 23% (Sagani, 2009).

As already mentioned, the amount of power generated by RES varies considerably on a daily, hourly and seasonal basis due to the change in the availability of sun, wind and other renewable sources. This variation means that power is sometimes unavailable, while in other cases there is surplus power. Therefore, the need to store energy for small to long periods is created.

The main economic service of pumping is that it improves the efficiency of the energy system by reducing the embedded uncertainty in the form of hedging the power supply deviation forecasts. In Greece, the total potential savings are 21 GWh, which accounts for approximately 2% of the total potential savings that could be enabled (JRC, 2013).

Today, the only reliable solution for large scale energy storage is provided by pumped storage systems and mainly by reversible hydroelectric systems whose energy conversion units are reversible, which means they can operate either as turbines (production phase) or as pumps (storage phase).

A typical repulsion system consists of the following parts:

- An individual pump or a pump system;
- An individual hydro-turbine or a hydro-turbine system;
- Two or more tanks, in a significant elevation difference;
- A pipe for pumping water from the bottom tank to the top;
- The same pipe or two parallel ones (see herein), for delivering water from the top tank down through the water turbine to generate electricity;
- An electric motor operating either as a motor or as a generator on a common shaft with the pump and the hydro turbine.

In a retrofit system we can distinguish two basic design versions: single pipeline and double pipeline, where there is independent piping for the turbine and the operation of the pumps.

From a first glance, a dual piping may be considered unnecessary, since if there is a need to generate power from the turbine and at the same time there is waste power from the thermal units or from the hydroelectric base units, then more energy could be directly absorbed by these units. However, this reasoning is incorrect due to network constraints. Actually the direct absorption of electricity can not happen beyond the energy grid.

At the same time, the time distribution of the rejected power indicates that the cut is first determined by the available energy output and secondly by the demand fluctuations. During peak demand time and at the same time excess power of the base units, on the one hand there is a power cut and a pump operation is required to exploit the excess power, on the other hand the turbine has to work (e.g. due to high demand). If the pump is running, it will take time for the turbine to stop and start, so the main advantage of the turbine's direct response is lost.

WIND ENERGY SYSTEM WITH PUMPED STORAGE

The application of wind turbines, along with a pumping system is of high interest. Particularly for the remote, unconnected Greek islands, characterized by high cost of electricity generation, heavy dependence on oil, and rich wind potential, wind power systems with pumped storage are a technically sound and economically acceptable solution.

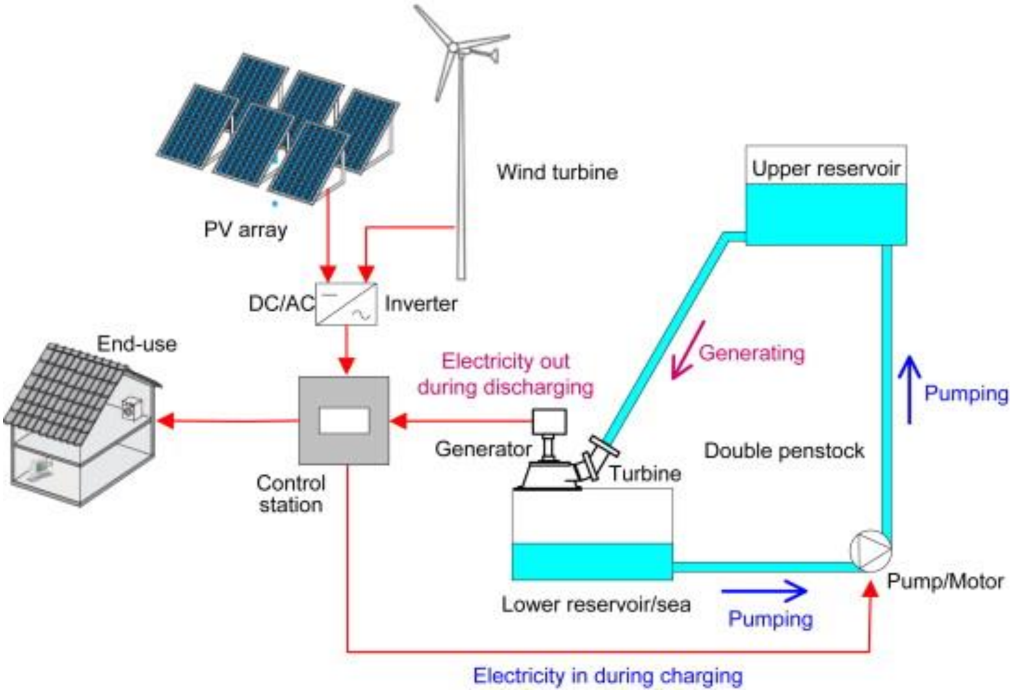


FIGURE 10: HYBRID ENERGY SYSTEM WITH PUMPED STORAGE (TAO MA, 2014)

The wind turbine system operates as follows: the wind farm produces electricity, which, as long as it cannot be directly absorbed by the grid, is utilized to pump the water from the bottom to the upper tank. Thus, electricity is transformed into a dynamic energy of water and stored in the upper tank. When it is necessary to convert this electricity to meet power needs (for example at peak demand or when wind is not blowing and there is electricity demand) then the reverse route is followed. The water will be transported from top to bottom, where a hydro-turbine will turn the water movement into electricity and re-route it back to the grid. The process is presented in Figure 10.

According to the Greek Regulatory Authority for Energy (RAE), the use of wind turbines along with a pumping system has many advantages. Indicatively:

- Such an application contributes to the utilization of wind potential and to the reduction of the operation of conventional oil plants. The intense fluctuations of wind energy are dealt with by the existence of the storage system and therefore better wind management and penetration of wind energy is achieved in the energy system. At the same time, the reliability of the electrical system increases with the incorporation of the hydro turbine, which is a fully controllable power generation system with a rapid response;
- As the price of fossil fuels is rising, the operation of such systems becomes competitive;

- Increasing the energy produced by wind farms has the effect of reducing CO_2 emissions. This means reducing the cost to PPC and private producers, which is obviously beneficial for consumers;
- Domestic production is greatly increasing and dependence on imported fuels (such as gas, oil, coal, etc.);
- There are significant social benefits as the project contributes to regional development and job creation;
- Hybrid hydroelectric systems can be combined with desalination a unit that uses wind power to produce potable water. This ensures the availability of water, not only for energy use, but also for water supply and irrigation.

The key disadvantage of a hybrid hydroelectric system is the cost of manufacturing it. The cost per MW of a hydroelectric plant varies between 2-3 million euros, compared with 1.3 million euros for a coal plant and 700.000 euros for a combined cycle (natural gas) unit. Although expensive in its construction, it is much cheaper to operate compared to conventional units, given the continuing increase in fuel prices.

In Figure 11, the operation of double piping pumped storage system is presented.

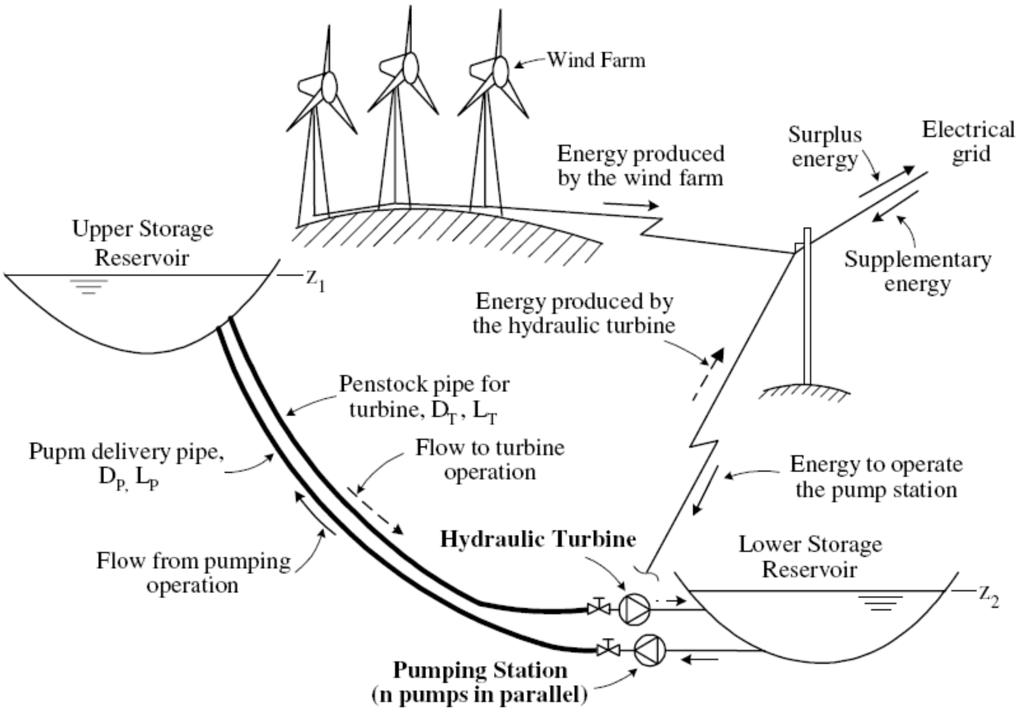


FIGURE 11: OPERATION OF DOUBLE PIPING PUMPED STORAGE SYSTEM (IBRAHIM AND ILINCA, 2012)

Generally, with regard to the interconnection of the wind energy system with pumping, we can distinguish two alternatives:

- "Direct connection" where the pumping system is connected to wind farms that will contribute to pumping with a network-independent transmission line. This connection is found on small or very medium-sized islands.
- The "indirect connection" where the pumping system is connected to the wind farms via the mains.

EXAMPLES OF HYBRID ENERGY SYSTEMS AROUND THE WORLD

SMALL-SCALE HYBRID ENERGY SYSTEMS

EL HIERRO ISLAND

El Hierro – the smallest island in the Canary Islands (278 km^2), which belongs to Spain and is located off the North African coasts – is powered by a wind energy system with pumped storage. The island has a volcanic origin, as it is the top of great alpine scenery, and is triangular in shape. The original volcano, El Golfo, collapsed because of gravity 130,000 years ago, resulting in the El Golfo Bay, which is 12 km in diameter.

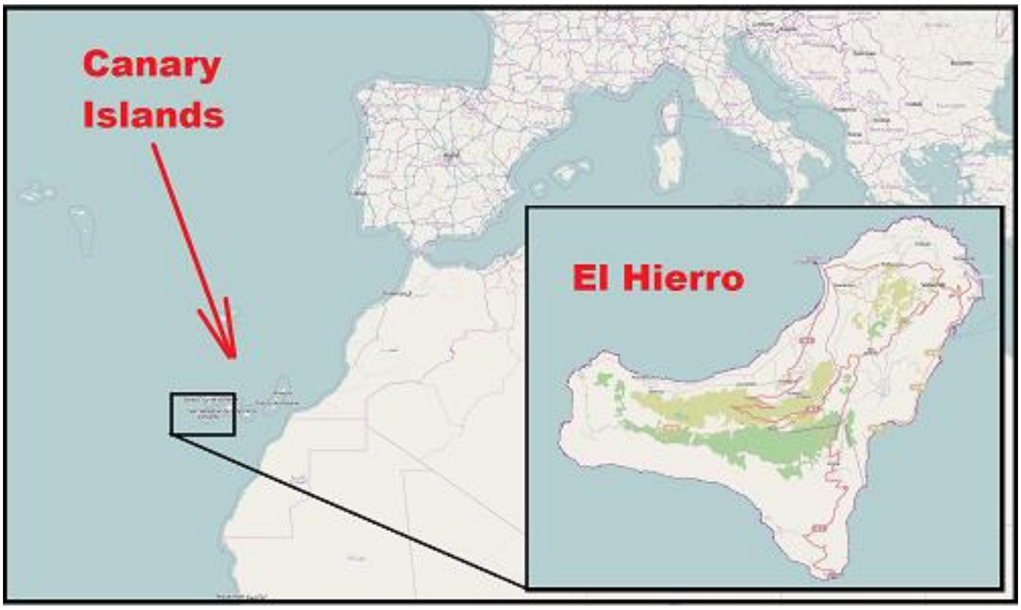


FIGURE 12: EL HIERRO ISLAND

Five wind turbines with a total capacity of 11.5MW, located at the northeastern end of the island, undertake the task of meeting the energy needs of 11,000 inhabitants with wind power.

The wind power surplus is used to pump water up to a large reservoir, 700 m above sea level, into a volcano crater in order to meet the energy needs in a period of apnea. The same water will follow the reverse pathway leading to a second tank at a lower altitude, after having crossed a series of generators to produce electricity.

The wind energy hybrid system with pumped storage costs €80 million and is estimated to help reduce carbon dioxide emissions by 18,700 tons per year, while reducing annual oil consumption on the island by 40,000 barrels.

The system covers 100% of the energy needs of the island's inhabitants. The pre-existing oil generator has remained in place to join the power supply system, in case of emergency.

Figure 13 shows the upper reservoir of the pumped storage system.

FIGURE 13: UPPER RESERVOIR OF THE PUMPED STORAGE SYSTEM

SAMSO ISLAND

Samso Island is located in Kattegat Bay in the North Sea, 15 km from the Jutland peninsula and belongs to Denmark. The population is about 4.300 inhabitants (2009 census), its area is 114 km^2, while annual energy consumption in 1997 amounted to 29.000 MWh.

In 1997 Samso won the Danish Ministry of Energy competition to create an energy-independent and "green" island. The aim of the program was to meet 100% of the island's energy needs from RES. within a decade, a fact that is a global innovation as it has not preceded similar work in the past. In order to achieve this ambitious goal, the actions that were to be taken were not only about the electricity sector, but more generally the energy profile of the island.

Saving energy and increasing efficiency in the electrical, heating and transport sectors, expanding the district heating network in combination with the use of local biomass reserves, expanding autonomous heating systems using heat pumps, solar panels, biomass facilities and the construction of onshore and offshore wind farms were some of the actions that had to be done.

FIGURE 14: SAMSO ISLAND

Samso is interconnected with the Jutland peninsula via a submarine cable, and the company NRGi is responsible for the distribution of electricity on the island. To ensure energy autonomy of the island, an installed capacity of 11 MW was needed. The 11 wind turbines of 1 MW each are placed in three groups and their hub height is 77 m.

The only manufacturer that produced wind turbines of this power and with such hub height was the company Bonus. The first wind turbine was installed in 2000, with a total investment cost of 8,8 million euros. In addition, ten offshore wind turbines of 2,3 MW were installed to compensate for CO_2 emissions in the southern part of the island, with a total investment cost of 33,3 million euros.

Overall, Samso's conversion program to a green island has to be seen as almost entirely successful, since it met most of the targets set. The primary goal of 100% energy autonomy through the use of RES was achieved in eight years, i.e. two years earlier than planned.

KYTHNOS ISLAND

It is worth noting that Europe's first hybrid energy system took place in Kythnos in July 1982. In 1982 the first wind park in Europe started its operation in Kythnos, consisting of five wind turbines of 20 kW power each. One year later, a PV station of 100 kW power was installed with battery storage of 400 kW. In 1989, the aforementioned wind turbines were replaced by five turbines of 33 kW power each, following the installation of a 500 kW Vestas wind turbine in 1998.

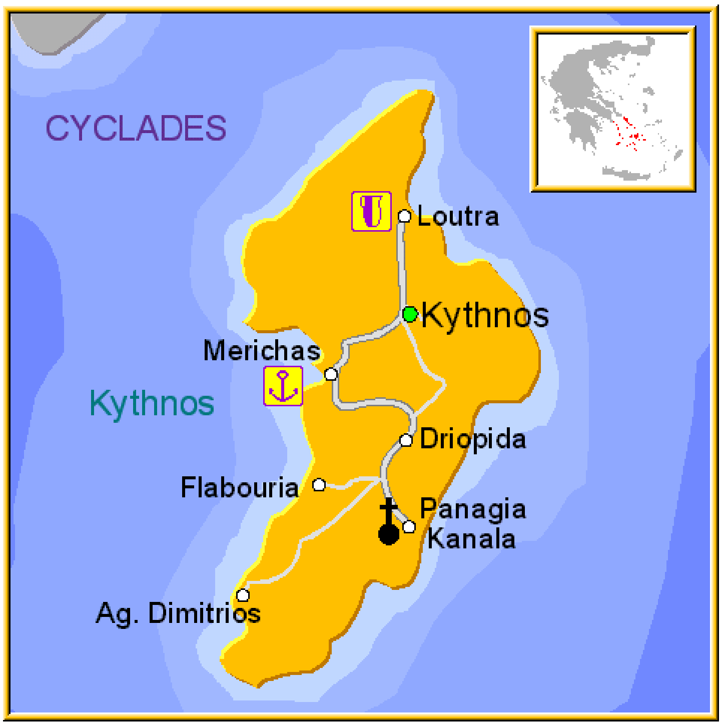


FIGURE 15: KYTHNOS ISLAND

Until June 2000, Kythnos comprised an oil power station of 2.120 kW and a 100 kW PV power station. In addition to the new hybrid system, the following equipment has been incorporated: 500 kW AC power, 600 kVA rotating capacitor, 400 kWh batteries, AC/500 kW load rejection resistors (initially 150 kW and increased to 500 kW in mid-June), and a supervisory and power management system (Figure 16).

Thus, with the old system, the network of Kythnos could not often absorb the energy that was generated from the 5 wind turbines and the 265 kW PV plant, now depending on the wind conditions, it will be able to absorb energy from RES up to 765 kW. With the new system, oil units are now out of service.

The penetration of RES is on average more than 25%, and if the capacity of the wind turbines increases to 1.500 kW, it is expected to exceed 50%, compared with about 10% so far, while demand needs are covered by the RES is 100% after the shutdown of all oil plants. It is noted that the penetration of RES in the Kythnos system reached its first months of operation up to 33%.

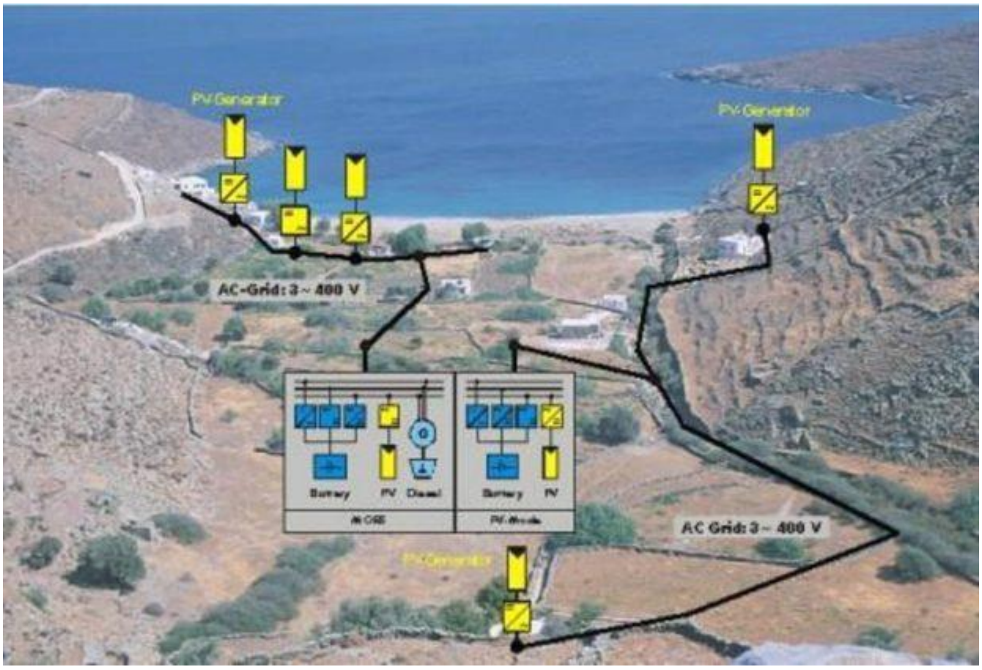


FIGURE 16: OPERATION OF KYTHNOS HYBRID ENERGY SYSTEM

With its inception, the intelligent hybrid production system of Kythnos has shown that it can fully meet its expectations. In a nutshell, the main goal of making wind energy a key source of energy and oil reserves, has greatly improved network stability and hence the quality of power supply and has generally significantly upgraded the entire energy system of the island. Its main advantages are:

- The change of roles between wind turbines and oil plants is now possible and occurs every time when the demand of the island is equal to or less than the supply of RES. There were cases where the shutdown of oil units lasted up to 12 hours;
- The reliability of the system is extremely high;
- The new system achieves more economical operation of the oil units as they are now loaded with a more stable load and close to the lower specific fuel consumption.

LARGE-SCALE HYBRID ENERGY SYSTEMS

NORWAY

A well-known country for its high mountain plateaus, abundant natural lakes and steep valleys and fjords, Norway’s topography lends itself perfectly to hydropower development. Indeed, hydro provided the basis for the nation’s industrialization in the late 19th century, and remains the backbone of its power system.

FIGURE 17: NORWAY

Hydropower regularly accounts for more than 95% of total Norwegian power production, with the small remainder made up by thermal and, only recently, wind. At the end of 2016, Norway's inland waters powered over 31 GW installed capacity, producing 144 TWh of clean power. It marks the highest annual hydropower generation ever recorded in Norway, which has been attributed to the very high rainfall throughout this year.

The Norwegian power system benefits from an integrated, open electricity market (Nord Pool), shared with neighboring countries (Sweden, Denmark, Finland, Estonia, Lithuania, Latvia). This extent of interconnections provides ample export opportunities for Norwegian hydropower. In 2016, taking advantage of the record-breaking production, Norway's net power exports reached 16,5 TWh, i.e., roughly 10% of total domestic demand (International Hydropower Association, 2016).

An essential prerequisite for the installation of new PHS capacity is the existence of sufficient cross-border transmission capacities, such that congestion plays a minor role in the decisions of export/import. As per today, the southern part of Norway has an exchange capacity amounting to 2.050 MW with Sweden, 950 MW with Denmark and 700 MW with The Netherlands.

In addition, the company which is in charge of the project, Statnett, implemented a project for a 700 MW cable between Norway and Denmark in 2014 (Statnett, 2013).

Moving even further in time, Statnett completed a project for a 1.400 MW cable between Tonstad, Norway and Germany by the end of 2018, and a 1.400 MW cable between Kvilldal, Norway and England that should be ready for operation by the end of 2020. In May 2013, Statnett applied for the concession for these two 1.400 MW cables (Lie 2013f). Moreover, Statnett is open for the possibility for another 1.400 MW cable between Norway and Germany (NorGer), and might be realized within a ten-year period after the launch of NORD.LINK (Lie 2013e). Statnett's two 1.400 MW cables to Germany and England gained support in the EU, as they were included in the EU Commission's list of 250 prioritized energy infrastructure projects in October 2013. In order to qualify for the list, the projects need to give significant advantages for at least two member countries, contribute to market integration, competition, and security of supply, and also reduce the CO_2 emissions (EnergiNorge, 2013).

In Figure 18, the transmission lines in south Norway are shown.

FIGURE 18: CROSS-BORDER TRANSMISSION LINES IN SOUTH NORWAY (STATNETT, 2011)

EXISTING LEGAL FRAMEWORK OF HYBRID POWER STATIONS

DEFINITION OF HYBRID POWER STATIONS

The legal framework that governs the installation and operation of hybrid power generation systems and, in particular that in non-Interconnected Islands is defined by law N.3468 / 2006, Government Gazette A'129. According to it, hybrid is called any power station that:

- Uses at least one form of RES;
- The total energy absorbed by the network on an annual basis does not exceed 30% of the total energy consumed to fill the storage of this plant;

- The maximum power output of the RES station units may not exceed the installed capacity of the storage units of this plant plus 20%.

For the production of electricity and high performance heat from RES, Combined Heat and Power (CHP) units are required. This permit is granted by the Minister of Development, following the opinion of the Regulatory Authority for Energy (RAE), based on the following criteria:

- National security;
- Protection of public health and safety;
- The overall security of the installations and related equipment;
- The energy efficiency of the project for which the application is submitted, as this results from the measurements of the RES potential (for RES projects), and from energy balances (for CHP plants);
- The maturity of the project implementation process, as it results from the studies that have been prepared, the opinions of the competent services, as well as other relevant data;
- Securing or securing the right to use the location of the project;
- The ability of the applicant to implement the project on the basis of its financial, scientific and technical competence. If the applicant is a newly created legal person, this possibility shall be assessed on the people who are part of it as partners or shareholders;
- Securing the provision of services of general interest and protection of customers;
- Environmental protection, in accordance with the legislation in force and the Special Framework for Spatial Planning and Sustainable Development for RES.

HYBRID ENERGY SYSTEMS IN NON-INTERCONNECTED ISLANDS

The existing legal framework provides detailed guidance on the operation of hybrid energy systems in non-interconnected islands. More specifically, it is stated that:

- The responsible operator is obliged to absorb, by priority, the electricity generated by the RES station of a Producer or an Autoproducer, as well as by the RES units of the hybrid station and, subsequently, the surplus of electricity produced by an autoproducer from a CHP station;
- The Transmission System Operator network shall prioritize, according to the previous paragraph, the electricity generation unit from RES hybrid plant to the other RES units if it participates in the provision of the guaranteed power

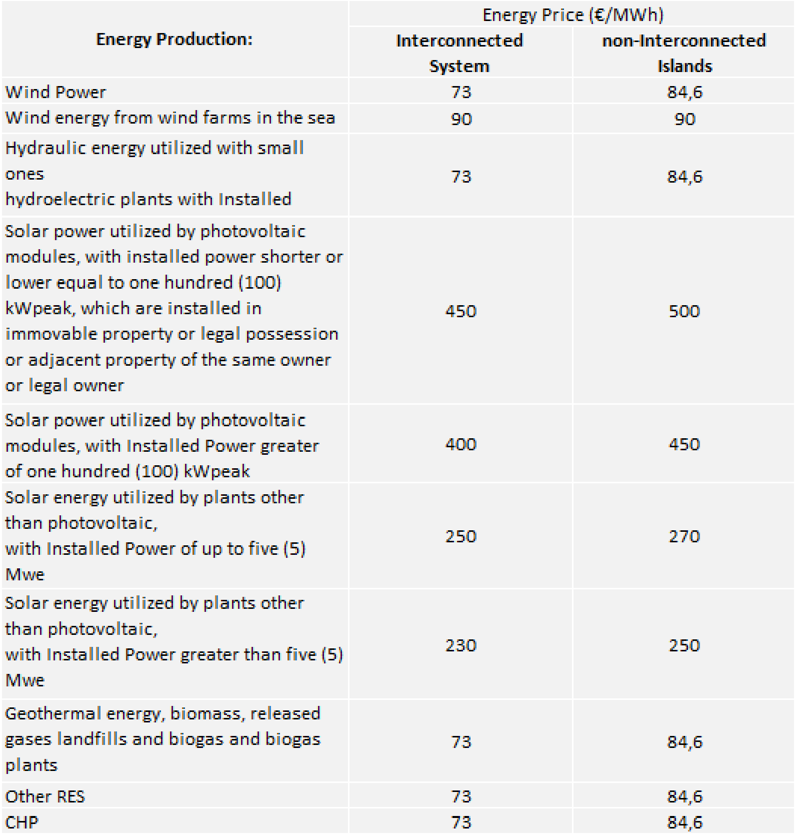
of the hybrid plant as provided for in the relevant production license or when the electricity is stored in the production plant of the hybrid station;

The Network Operator, when allocating the load, gives priority to the controlled production units for the utilization of the stored energy of the hybrid station, compared to the associated conventional units.

ELECTRICAL ENERGY PRICING OF HYBRID SYSTEMS

Electricity produced by Producers or Auto-producers through a power plant from RES or CHP or through a Hybrid Station and absorbed by the System or the Network is priced on the basis of the price in Euros per MWh of the electricity absorbed by the System or the Network, including the Non-Interconnected Islands Network.

The pricing of electricity in the previous case is based on the data in the Table 1. The prices for electricity generators apply only to RES and CHP stations with an installed capacity of up to 35 MW and the surplus of electricity available to the system or the network, which may account for up to 20% of the total electricity produced by these plants on an annual basis.



Energy Production:	Energy Price (€/MWh)	
	Interconnected System	**non-Interconnected Islands**
Wind Power	73	84,6
Wind energy from wind farms in the sea	90	90
Hydraulic energy utilized with small ones hydroelectric plants with Installed	73	84,6
Solar power utilized by photovoltaic modules, with installed power shorter or lower equal to one hundred (100) kWpeak, which are installed in immovable property or legal possession or adjacent property of the same owner or legal owner	450	500
Solar power utilized by photovoltaic modules, with Installed Power greater of one hundred (100) kWpeak	400	450
Solar energy utilized by plants other than photovoltaic, with Installed Power of up to five (5) Mwe	250	270
Solar energy utilized by plants other than photovoltaic, with Installed Power greater than five (5) Mwe	230	250
Geothermal energy, biomass, released gases landfills and biogas and biogas plants	73	84,6
Other RES	73	84,6
CHP	73	84,6

TABLE 1: ENERGY PRICING OF HYBRID SYSTEMS (SOURCE: RAE)

NON-INTERCONNECTED ISLANDS

ABOUT NON-INTERCONNECTED ISLANDS

Most islands currently in Greece (mainly in the Aegean) are powered by stand-alone electrical systems, mainly comprising local thermal power stations, which run on oil, heavy or light, and RES stations (wind and photovoltaic). These islands have not been connected to the mainland electrical system so far, mainly due to technical difficulties that have existed so far, but also because of financial difficulties, as interconnections are capital intensive projects.

The non-interconnected Islands electricity market consists of 32 autonomous systems. Some of them consist of more islands (complexes of islands), and the operation and management of the Market of the Non-Interconnected Islands is made by HEDNO SA (Island Management Division).

The magnitude (peak demand) in kW of these systems varies:

- 19 "small" stand-alone systems have peak demand of up to 10 MW.
- 11 "medium-sized" stand-alone systems have a peak demand of 10 MW to 100 MW.
- 2 "large" autonomous systems have a peak demand of more than 100 MW, i.e. Crete and Rhodes.

Similarly, the electricity demand in the Non-Interconnected Islands also varies from a few hundred MWh to the smaller islands (e.g. Antikythira, Agathonisi, etc.) up to some TWh in the largest one (Crete).

NON-INTERCONNECTED ISLANDS CODE

The particular geographical situation of the Greek island network with many isolated and small electrical systems creates a number of problems that have to do mainly with the production of electricity, as well as the adequate and safe electrification of the Non-Interconnected Islands. For this reason, it is necessary to have a Code that ensures the smooth, uninterrupted, safe and efficient operation of the Non-Interconnected Islands Network.

The drafting of such a Code is a prototype project as there is no equivalent or similar in the world due to the geographic specificity of the Greek island network and because it had to formulate and incorporate rules for the following:

- The need to fully implement the rules of the European Directives for the purchase of electricity in many, small and different size island systems;

- The significant penetration of RES in these island systems by RES technologies and controlled production technologies expected to develop in the islands (solar, thermal, etc.);
- The need to integrate the legal framework for hybrid and solar thermal plants;
- The inability to apply the established rules of operation of a developed electricity market due to the extremely limited number of producers participating in price formation;
- The operation of this market through the provision of services of general interest (SGI) and the need to contain the total cost of production, which now costs the consumers of the territory with an amount of approximately 600 million € per year (SGI for non-interconnected islands). Also, the necessity and obligation to provide sufficient documentation of this annual cost;
- The need to design, on a non-existent basis, an integrated system for the management, supervision and control of local Systems and the Market, as well as the difficulty of implementing the relevant regulations due to the main infrastructure and human resources deficiencies;
- The need to simplify procedures where necessary without reducing the benefit to end-users and / or market participants of the market.

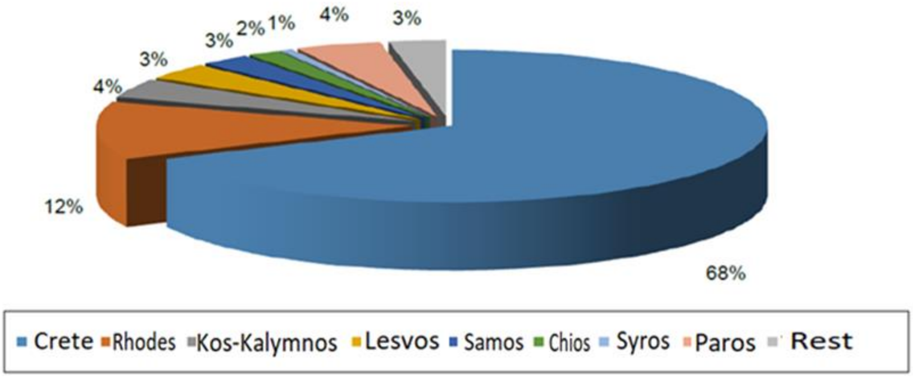
The Non-Interconnected Islands Code is being implemented gradually, after a five-year transition period. This period is considered necessary for the progressive development and installation of the necessary infrastructure (Centers for Energy Control, Information System, etc.) as well as for the management of the Systems and Market, which will be implemented on a zero basis by HEDNO SA.

From the definitions contained in this Code, the main ones are distinguished:

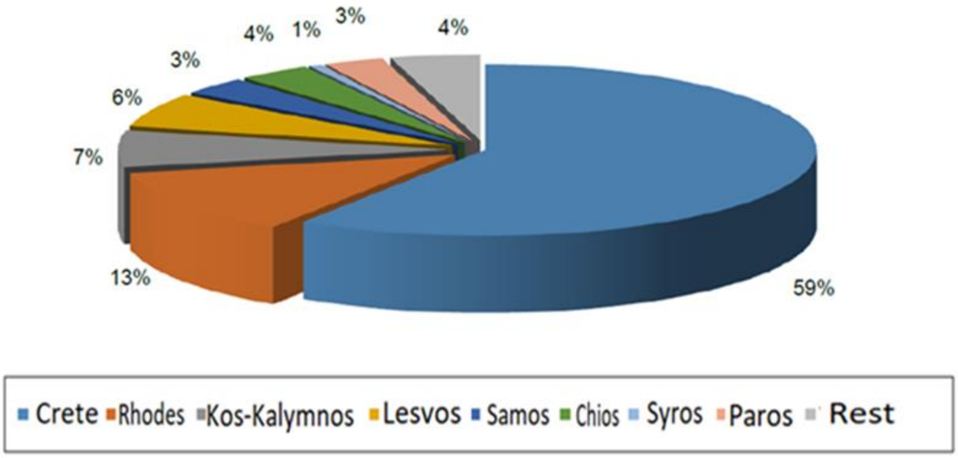
- ***Non-Interconnected Islands Market:*** *The set of processes, activities and transactions that take place in each Non-Interconnected Island System and relate to the planning of its development and operation, the monitoring and control of its actual operation, the settlement of payments in order to secure, uninterrupted and in the most economical way of electrifying its consumers.*
- ***PCC (Power Control Centers) of Non-Interconnected Islands****: The PCCs manage the electrical systems as well as their basic programming functions, such as the preparation and execution of the Dispatch programs, the communication with the Non-Interconnected Islands Network users, the monitoring and the control of the Non-Interconnected Islands systems, the recording and storage of the operational elements. They are distinguished in Local PCCs and in the Central PCCs. The Central PCC is installed in the Non-Interconnected Island Operator while the local PCC is installed on each electric system (on each island or island complex).*

- ***Rolling Daily Energy Planning (RDEP):*** *Production planning of all Production Units to cover the load for the 24 hours of the next day (Dispatch Day), which is compiled and executed in two 12-hour subperiods of the Dispatch Day (1st and 2nd RDEP Period). RDEP is necessary to securely meet the demand for each electrical system, by observing the operational rules and security restrictions provided by the Code.*
- ***Network Users:*** *a) Producers, whose power plants are connected to the Network, b) Load Representatives and c) "Consumers" whose facilities are connected to the Network to absorb electricity.*

Graphs 2 and 3 illustrate the distribution of RES energy generation in the non-interconnected grid.



GRAPH 2: DISTRIBUTION OF GENERATION OF 98W/P ON NON-INTERCONNECTED ISLANDS



GRAPH 3: DISTRIBUTION OF GENERATION FROM 1.758 PV STATIONS ON NON-INTERCONNECTED ISLANDS

The Manager is required to ensure reliable and cost-effective energy, development and technical excellence of production, protection of the island's environment, ensuring the necessary space for new production potential. At the same time, he must abstain from any discrimination between producers of Non-Interconnected Islands and draw up and submit for approval the Development Plans as foreseen.

The Manager shall ensure that all necessary measures are taken to design, develop, support, maintain and operate the facilities and equipment necessary for the sound and efficient management and operation of the Market and Non-Interconnected Islands systems, in accordance with the provisions of the Code. The Manager shall ensure that all necessary measures are taken and that all necessary resources are available to maintain high-quality services to System Participants and Users and to the Network, and at least to the level described in the Code.

For its part, each participant is required to keep the necessary accounts and to pay in due time his debts to the Manager, to ensure the smooth operation of his facilities, to assist in the more efficient and proper functioning of the Market, as well as to ensure rehabilitation damages of the necessary equipment.

In addition, the Code provides rules for the integration and operation of the RES/CHP stations in order to maximize the penetration of the generated electricity from these units in safe conditions for the system. Table 2 summarizes the information derived from the Information Sheet published by HEDNO SA for September 2016.

Non-Interconnected Islands Network	Energy Generation (MWh)		
	Wind Parks	**PV**	**RES Total**
Crete	52.666,00	13.018,00	65.684,00
Rhodes	9.493,00	2.738,00	12.231,00
Kos	3.140,00	1.528,00	4.668,00
Lesvos	2.739,00	1.411,00	4.150,00
Samos	1.997,00	738,00	2.735,00
Chios	1.298,00	786,00	2.084,00
Syros	523,00	145,00	668,00
Paros	3.428,00	652,00	4.080,00
Rest of Network	2.266,00	962,00	3.228,00
Total	77.550,00	21.978,00	99.528,00

TABLE 2: RES ENERGY GENERATION ON NON-INTERCONNECTED ISLANDS (SEPTEMBER 2016)

CHAPTER 3: STUDY AREA

GENERAL CONTEXT ABOUT IKARIA

Ikaria (or Nikaria) is one of the largest islands in the eastern Aegean (Figure 19), with 255 km^2 in extent and 160km long coastline. Its population is 8,423 inhabitants, according to the 2011 census. Administratively with Fourni is the homonymous regional unit of the Region of the North Aegean. The capital of the island is Agios Kyrikos with 3,243 inhabitants on the southeastern side, with Evdilos on the north side being the second largest pole on the island.

Ikaria had been inhabited since the Neolithic era, before 7,000 BC, by residents whom the ancient Greeks called the Pelasgians later. Around 750 BC, Greeks from Miletus colonized Ikaria by establishing facilities in the region now called Kambos, which they then called Oenoi for its wine. In the 6th century BC Ikaria merged administratively with Samos and was part of Polycrates' sea empire.

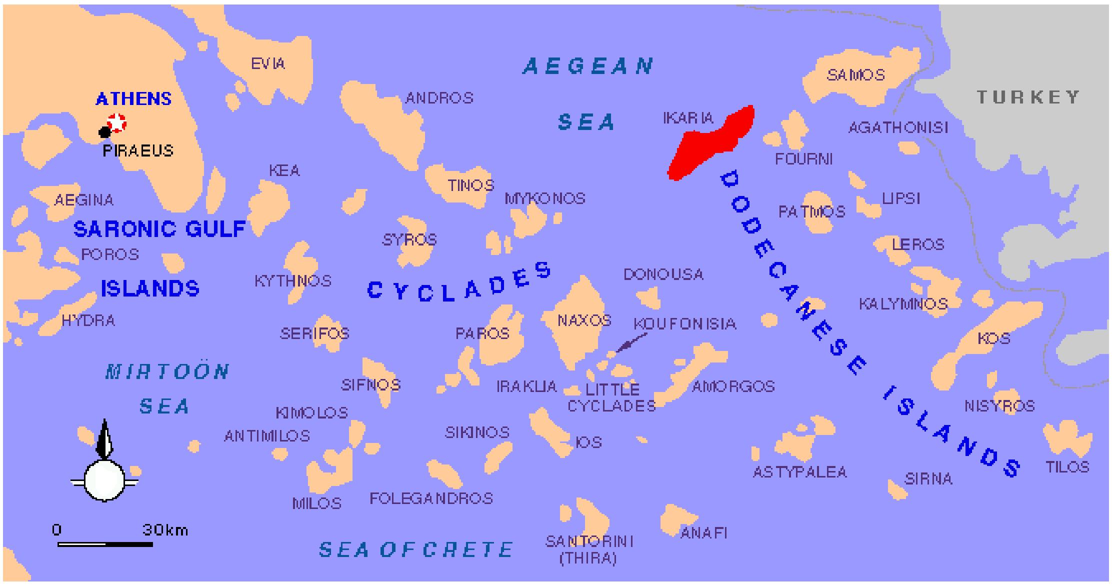


FIGURE 19: LOCATION OF IKARIA ISLAND

Ikaria was named after Ikarus, son of Daedalus. Ikarus fell on the rocks of Ikaria when the sun melted the wax on his wings. Ikaria belongs to the Prefecture of Samos and is inhabited since the 9th B.C. century. It was, indeed, a member of the Athenian alliance.

Ikaria has been inhabited since prehistoric times, but interest begins to show from 15th century, a century marked by pirate attacks on the Aegean coast. Then the Genoese despots leave the island and are fortified in Chios, with the Ikarians to escape to the mountains. So begins the era flourishing Lagada, a craggy village at the western end of the island above the promontory of Cape Pope built in a hidden mountain valley. Here was the "Ark of the Ikarian survival" for inhabitants.

Ikaria has been overwhelmed in the past by pirate raids. For this reason, they built anti-pirate villages, such as Lagada.

In 1912 the people of Ikaria themselves rebelled and won their independence from the Turkish administration, establishing the Ikarian State with its own coin and stamp and later on, with the arrival of the Greek fleet, it joined with Greece.

At the time of the Civil War, the island was a place of exile for dissidents, embraced by incompetent residents.

FIGURE 20: IKARIA ISLAND

The island is mostly mountainous, as shown in Figure 20. Athera of Ikaria, also known as Pramnos, is the small mountain range that forms the backbone of the island, crossing it lengthwise. The highest peak of the Athera is Fardi, which has an altitude of 1,041 m. At a similar height, there are two other peaks, Melissa (1,031 m) and Erifi (1,026 m). Below the thousand meters we find the peaks of Ammoudia (913 m), Ypsonas (697 m) and others. The landscape has contrasts, with steep rocky locations and, on the contrary, places with dense woods and other vegetation.

According to geological data of Institute of Geological Studies of Greece, Ikaria consists of metamorphic rocks (e.g. gneisses), which are crossed by granites. Specifically, the area of implementation (Raches municipality) of Ikaria’s HES, located in the western part of the island, consists exclusively of granite and granite covering about half the area of the island (Patsidis, 2012).

The climate of Ikaria falls under the climatic type of the Mediterranean Coast (Csb by Köppen), a dry and relatively hot summer with wet and mild winters. Ikaria is considered one of the islands with the largest wind potential (Figure 21), with an average annual wind speed of 7.5 m/s at an average altitude (National Meteorological Service's climate report). This is mainly due to the strong summer northern winds, also known as ''meltemia''.

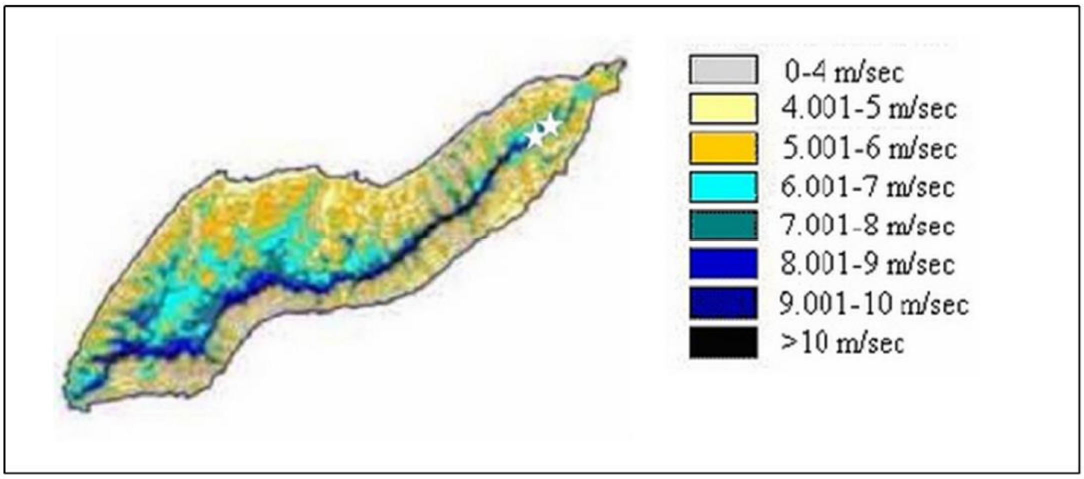


FIGURE 21: WIND POTENTIAL OF IKARIA

Ikaria's irrigation water needs are estimated to be up to 570,000 m^3/year. About 448,000m^3/year are offered in the northwestern part of the island by the Pezi dam, while the needs for water supply amount to 700,000 m^3/year. The losses of the island's water supply network are of the order of 30%. An important role in the water supply of the island is played by natural sources and existing drilling in the eastern, central and western Ikaria (Kritikou, 2005). We note that the natural sources and drilling in the area of construction of the hybrid project were not taken into account when simulating hydrological processes, due to lack of detailed data.

ABOUT THE HYBRID ENERGY SYSTEM

The idea of implementing the hybrid energy project in Ikaria, named NAERAS, belongs to the Public Power Corporation (PPC) and the Development Company of the former municipality of Raches, which in 1999, in cooperation with European companies, applied a financial proposal to the European Commission. The proposal was accepted, but the whole venture has not been successful.

Later, appreciating the value of the project, PPC proceeded with the planning and tender studies, with the assistance of the National Technical University of Athens (NTUA) in the design of the electrical network. In 2006, the Declaration of the

Convention was approved and the competition took place. In 2008, the construction contract was signed with the Contractor Company ENET SA.

In November 2009, the Regulatory Authority for Energy (RAE) submitted an application for transfer of the Production License of the project, adapting its operation in the existing institutional framework for hybrid plants, based on a study prepared by the NTUA. The sale price of hybrid energy was set by RAE equal to 295 €/MWh (PPC RENEWABLE SA, 2012).

The original plan of the hybrid energy system of Ikaria includes:

- Pezi dam;
- two water tanks;
- two wind parks;
- a pumping station;
- an autonomous power station.

The total cost of the hybrid energy project is approximately €40,000,000, which includes construction and supervision costs for all aforementioned works, expenses for the construction of new roads and the improvement of the existing area, as well as for the upgrading and reconstruction of the island's electricity network.

PEZI DAM AND WATER TANKS

The reservoir Pezi is located about 3.7 km southwest of Christos. It was created by the construction of a dam at the river Halaris. It is an artificial indoor wetland area of 110.1 acres.

The wetland is located within an area assigned as a Special Protection Area, an Important Area for Birds and a Landscape of Special Nature (Government Gazette 591/B/15-5-2002). Wetland activities are limited, with intense grazing prevailing. Activities in the catchment area are also mild with grazing and forestry dominants. It presents rich vegetation around the lake, mainly with trees, with rough pine trees and plane trees, dominating all over the area, as well as alder and wheat.

Pezi dam was constructed in the municipality of Raches, Ikaria, in the Pezi area, where it was named after since 1995. The dam is an earth dam with clay core. The initial useful volume was 1,000,000 m^3, which due to adhesions and sludge was reduced to 910,000 m^3. For the sealing of the reservoir no additional dikes and special constructions were required, since the granite, the rock on which the dam was built, contributes itself in the physical tightness of the reservoir. The height of the embankment is 29 m, the length of the crown is 235 m and the width of the crest is 10 m. The volume of dyke used was estimated up to 163,100 m^3 and the total construction cost of the project is estimated at €4,223,000.

Figures 22 and 23 show characteristic photos from the dam of Pezi.

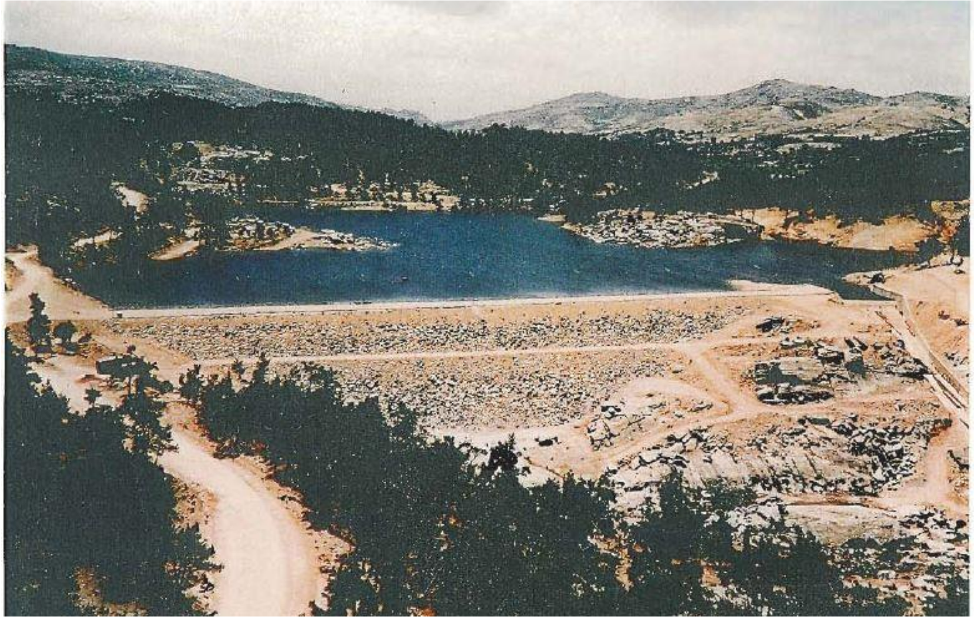


FIGURE 22: GENERAL VIEW OF PEZI DAM

FIGURE 23: PEZI DAM (SOURCE: PPC SA)

The hybrid scheme includes two man-made tanks, up (Ano Proespera, Figure 24) and down (Kato Proespera, Figure 25), each with a capacity of 80,000 m^3, which will be filled by the spill of the already existing irrigation reservoir in Pezi. The upper hydroelectric plant, with a capacity of 1 MW, will be located upstream of the upper tank, to receive the spill from the reservoir, while the second station of 3.1 MW will be located upstream of the lower tank. The latter station is reversible, thus allowing water to be lifted from the lower to the upper tank, through a pumping station comprising 12 pumps of 250 KW each.

FIGURE 24: ANO PROESPERA TANK

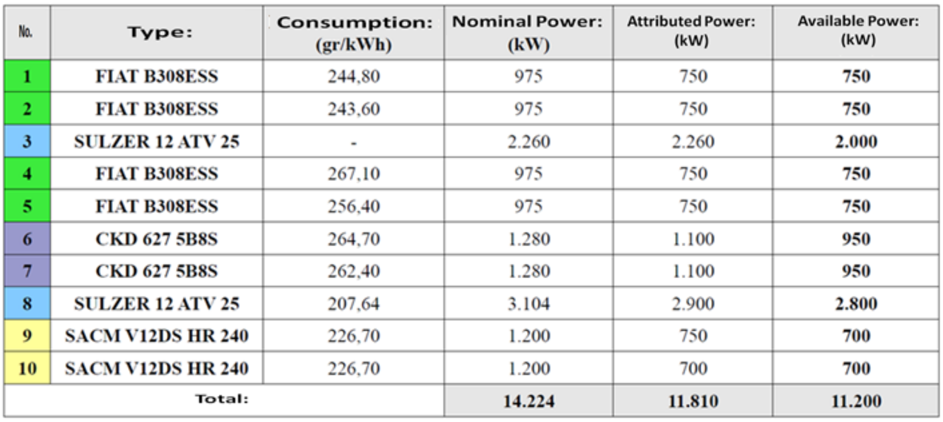
FIGURE 25: KATO PROESPERA TANK

The maximum elevation of the reservoir (crest level) is 721 m, while the two reservoirs are set at 543 m for the top and 50 m for the bottom. The length of the pipes from the dam to the upper tank is 3.500 m, while the length from the top to bottom tank is 3.060 m. In case of pumping from the bottom to the top tank, the length is estimated at 3.100 m.

AGIOS KIRIKOS POWER STATION

It is a thermal power station owned by PPC, with oil-operated rotary internal combustion engines. The station is 1 km west of Agios Kirikos, on the south side of the island. Its facilities include production machines, tank systems, a seaside pumping station, medium voltage equipment, warehouses and machining. Each machine is called a unit or a Power Generator, because it combines a diesel engine and an electric generator. Petroleum units have a yield of up to 40% or 50% and start fast in relation to other types of thermal machines but with a disadvantage of expensive fuel.

Nominal power is the point of operation with maximum efficiency and lower fuel consumption. It is very close to the maximum theoretical power a unit can reach. The power output is the actual electrical power that is attributed at this time, with the unit's own power consumption. The total rated power of all installed units is around 15 MW (Table 3).



No.	Type:	Consumption: (gr/kWh)	Nominal Power: (kW)	Attributed Power: (kW)	Available Power: (kW)
1	FIAT B308ESS	244,80	975	750	**750**
2	FIAT B308ESS	243,60	975	750	**750**
3	SULZER 12 ATV 25	-	2.260	2.260	**2.000**
4	FIAT B308ESS	267,10	975	750	**750**
5	FIAT B308ESS	256,40	975	750	**750**
6	CKD 627 5B8S	264,70	1.280	1.100	**950**
7	CKD 627 5B8S	262,40	1.280	1.100	**950**
8	SULZER 12 ATV 25	207,64	3.104	2.900	**2.800**
9	SACM V12DS HR 240	226,70	1.200	750	**700**
10	SACM V12DS HR 240	226,70	1.200	700	**700**
	Total:		**14.224**	**11.810**	**11.200**

TABLE 3: INSTALLED UNITS IN THE AUTONOMOUS POWER STATION OF IKARIA

WIND PARKS

The installed wind power of Ikaria includes a wind farm in the hill area of Stravokoundoura (Figure 26), at an altitude of 800 m, consisting of three Enercon E-44/900 of 900 kW each one, and a hub height of 55 m, and a horizontal axis Enercon E-40/600 wind turbine, of a nominal power of 600 kW, at Kefalas Hill in the village of Perdiki at an altitude of 596 m. In addition, the Stravokoundoura wind park includes an underground building, hosting a SCADA system, a 30kVA backup power generator and voltage substation equipment.

In the past, PPC also planned to construct a pilot wind farm in the neighboring Firinaspa location. This included 7 asynchronous wind turbines, of 55 kW each, thus a total capacity of 385 kW. It has been phased out and is out of service since 2006.

In Figure 27, the power curve of the wind turbine of the Stravokoundoura wind park is presented.

FIGURE 26: STRAVOKOUNDOURA WIND PARK

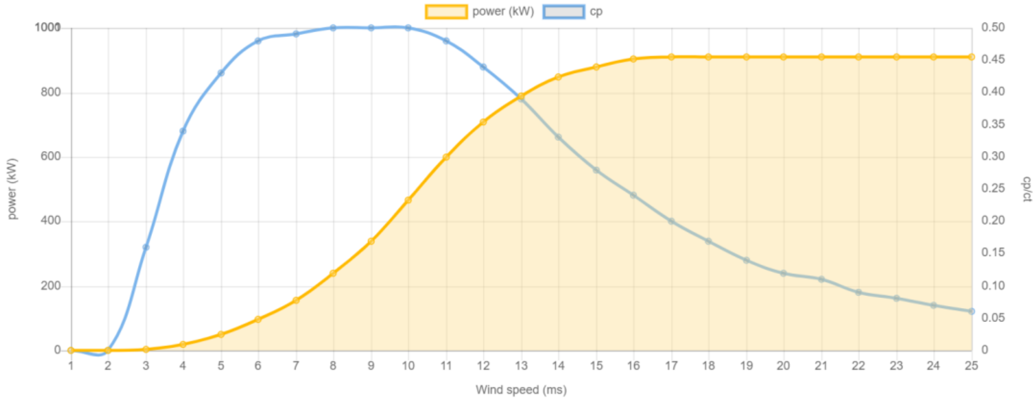


FIGURE 27: ENERCON E-44/900 POWER CURVE

KATO PROESPERA PUMPING STATION

Close to the bottom tank, there is the pumping station that returns the water back to the upper one, through an individual pipe. It includes a 30,50×12,00 m building, where eight assemblies consisting of multistage centrifugal horizontal axis pumps, delivering 85 m^3/h at a maximum net head of 521,0 m will be installed. Pumps are of variable speed and fit according to the desired pumping power.

In Figure 28 the top view and the section of the pumping station is shown, and in while its pumps are show in Figure 29.

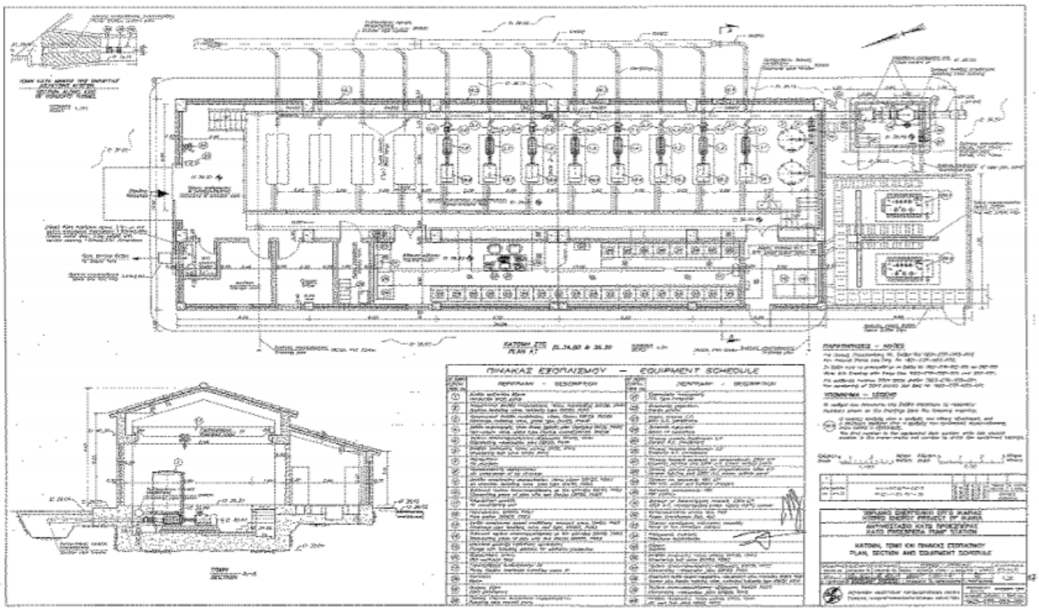


FIGURE 28: TOP VIEW AND SECTION OF THE PUMP STATION

FIGURE 29: PUMPING STATION'S INTERIOR

CHAPTER 4: INPUT DATA

The simulation model of the Hybrid Energy System of Ikaria runs in hourly time step and uses as input data:

- Runoff data (inflows to Pezi reservoir)
- Wind data
- Energy Demand Data
- Irrigation Demand Data

RESERVOIR INFLOW DATA

The available information about the inflows to the Pezi reservoir, i.e. the runoff produced by the upstream catchment, is very limited. Specifically, the existing data only includes daily observed inflows for 30 months, from 01/05/1997 to 31/12/1999.

Therefore, it was necessary to develop a hydrological model to represent the key processes of the water balance across the catchment. This model receives rainfall and potential evapotranspiration data, and converts them to runoff at the catchment outlet, i.e. upstream of the dam. Its operation is shown in Figure 30. The predictive capacity of the hydrological model is evaluated by means of convergence of the observed and modeled runoff.

Key assumption of the water balance model is the treatment of maximum potential retention as varying quantity during the simulation period. This quantity, symbolized S_t, denotes the empty space of a conceptual tank of capacity K, employing the soil moisture accounting. This tank represents the unsaturated zone, which transforms the infiltrated rainfall into actual through the soil, interflow and percolation to deeper zones. The runoff is considered the sum of three components, i.e. the flow through the unsaturated zone (interflow), the underground flow (baseflow) and the surface flow (surface runoff).

Model inputs at each time step are the daily precipitation over the basin, P, and the daily potential evapotranspiration, PET. The latter can be estimated with high accuracy using as inputs the air temperature, the solar radiation, the relative humidity and wind velocity However, due to lack of such measurements in Ikaria, we employed the following simplified radiation-based expression (Tegos *et al.*, 2013):

$$E = a\, R_a / (1 - c\, T) \qquad \text{Eq. (1)}$$

where E is the evaporation (or potential evapotranspiration) in mm, R_a (kJ × m^{-2}) is the extraterrestrial radiation, T (^{o}C) is the mean air temperature, and a (kg × kJ^{-1}) and c (^{o}C^{-1}) are model parameters that are inferred through calibration.

In order to run the model, it is essential determining the soil moisture storage at the beginning of each step. By adding this quantity to the maximum potential retention we get the storage capacity of the soil moisture accounting tank, K. The maximum potential retention is estimated on the basis of the dimensionless runoff curve number, CN, here considered is a model parameter, using the well-known empirical formula by SCS.

At the beginning of each time step, we estimate the direct evapotranspiration as the minimum between the available rainfall and potential evapotranspiration, i.e.:

$$\mathrm{ET}_{\mathrm{direct}} = \min\,(\mathrm{PET}, P) \qquad \text{Eq. (3)}$$

Then we estimate the surface (overland) runoff as:

$$Q_{sur} = (P - \mathrm{ET}_{\mathrm{direct}})^2 \,/\, (P - \mathrm{ET}_{\mathrm{direct}} + K - S) \qquad \text{Eq. (2)}$$

where $K - S$ represents the so-called maximum potential soil retention. The surface runoff is propagated to the basin outlet via a liner reservoir routing approach, using a recession parameter, ϑ.

The remaining quantity (rainfall excess) enters the soil moisture tank, thus increasing its current storage to:

$$S = S_0 + P - Q_{\mathrm{overland}} - \mathrm{ET}_{\mathrm{direct}} \qquad \text{Eq. (4)}$$

If the direct evapotranspiration is less than the potential value, PET, additional water is abstracted from the available soil moisture, by means of soil evapotranspiration. The estimation of the latter is based on the well-known Thornthwaite formula, i.e.:

$$\mathrm{ET}_{\mathrm{soil}} = S\,\{1\ - \exp[-\,(\mathrm{PET} - \ \mathrm{ET}_{\mathrm{direct}}) \,/\, K\} \qquad \text{Eq. (5)}$$

Thus, the actual evapotranspiration is the sum of the direct evapotranspiration and the soil evapotranspiration through the unsaturated zone.

Next, the interflow across the unsaturated zone is calculated as the product of the recession rate, λ, and the soil moisture storage above a threshold, H_0, i.e.:

$$Q_{\mathrm{interflow}} = \max\,[0, \lambda\,(S - H_0)] \qquad \text{Eq. (6)}$$

The soil storage is calculated depending on the soil moisture storage at the beginning of the time interval, the daily precipitation, the surface flow and the direct evapotranspiration. In case that the interflow threshold is greater than the storage, the flow of the unsaturated zone equals zero.

Finally, another portion, μ, of soil moisture storage, moves vertically, to feed the groundwater tank, thus representing the percolation process.

For the representation of groundwater processes we consider a lower tank of infinite capacity, which gets as input the percolation from the upper zone and has two outputs, i.e. the baseflow and the underground losses, which are controlled by two recession parameters, i.e. φ and ξ, respectively.

The above model uses seven parameters, i.e. the runoff curve number, CN, the interflow threshold H_0, and the five recession coefficients (ϑ, λ, μ, φ, ξ).

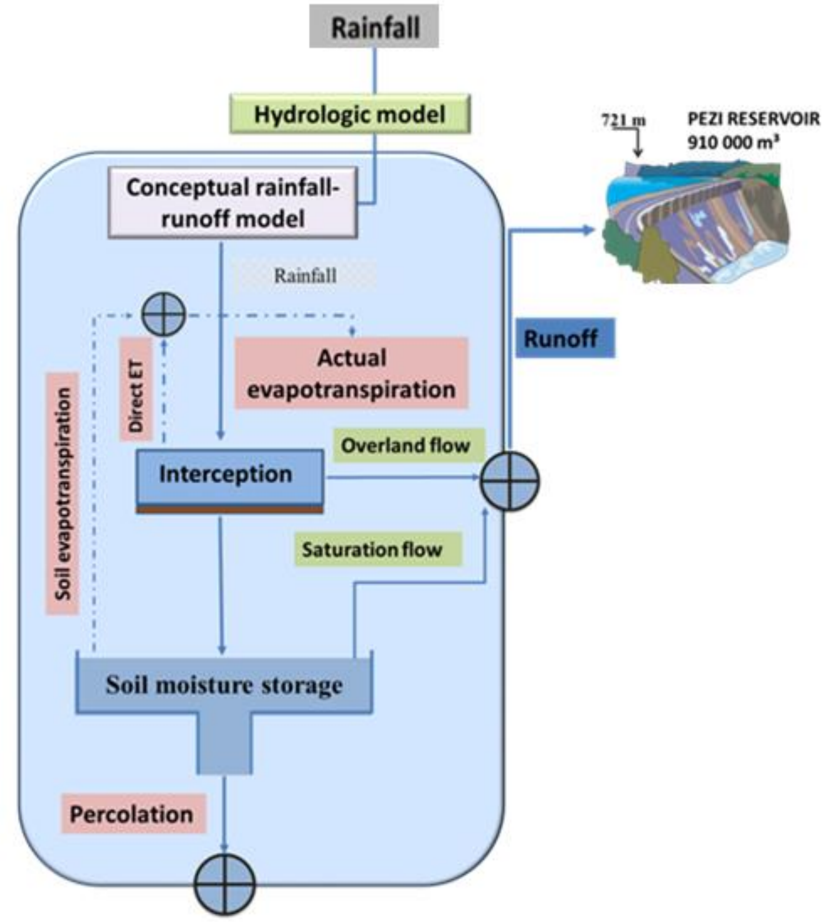
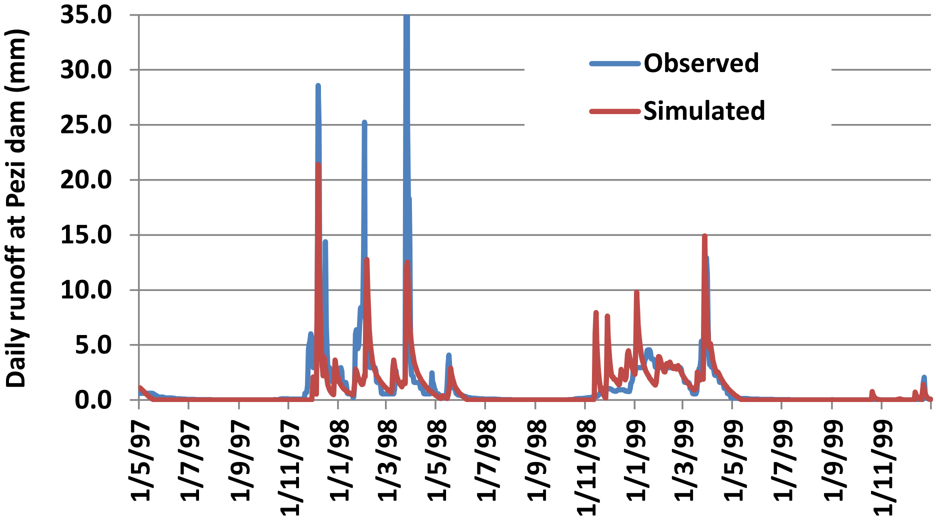


FIGURE 30: OPERATION OF THE HYDROLOGICAL MODEL

Every model requires a quantitative measure of performance, while in a hydrological model it is essential to predict the hydrograph peaks correctly. In order to achieve the calibration of the hydrological model in an attempt to improve its predictive capacity, during every time step of the simulation the square error of the observed and simulated runoffs is being calculated. Therefore, the definition of the optimal values of the model parameters comes out of the minimization of the square errors' sum. The outcomes of this procedure are shown in Graph 4.



GRAPH 4: COMPARISON OF SIMULATED VS. OBSERVED RUNOFF

WIND DATA

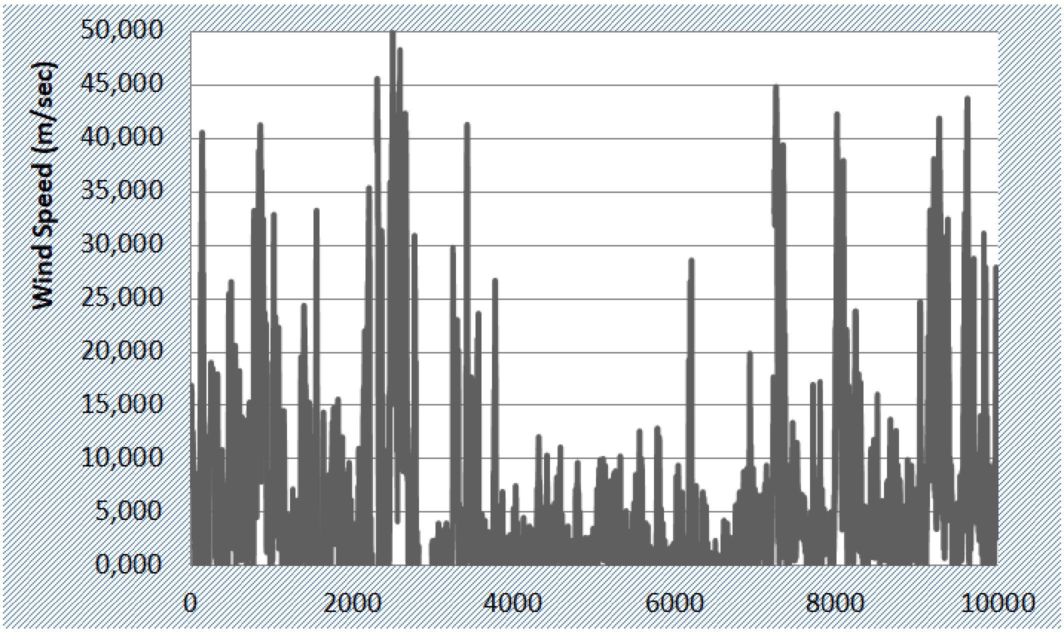
HISTORICAL DATA

Ikaria is one of the Aegean islands with the largest wind potential, which is mainly due to the strong summer winds, also known as ''meltemia''. The raw (10-min) wind data from Raches station has duration of seven years, and was provided by the National Observatory of Athens (Dr. Vassiliki Kotroni and Dr. Kostas Lagouvardos, personal communication). The mean value of the wind speed at the measured altitude is calculated at 5,4 m/s, with standard deviation 6,6 m/s. In Graph 5 a wind speed representation is illustrated for a time interval of 10.000 hours, exhibiting an apparently large variability.

The following formula is used to convert the wind speed from the altitude to that of wind farm operation:

$$\frac{u_2}{u_1} = \frac{\ln \frac{z_2}{z_0}}{\ln \frac{z_1}{z_0}} \qquad \text{Eq. (7)}$$

The altitude of the wind turbine in Stravokoundoura (800 m) is considered as z_2 in the equation above, z_1 the wind speed measurement altitude (5 m) and z_0 empirically set equal to 0,1 m. By applying this formula, an adjustment coefficient of velocity equal to 1,61 was obtained, to convert the wind speed (u_1), measured at 5 m above the ground, to the height hub (i.e., 55 m).



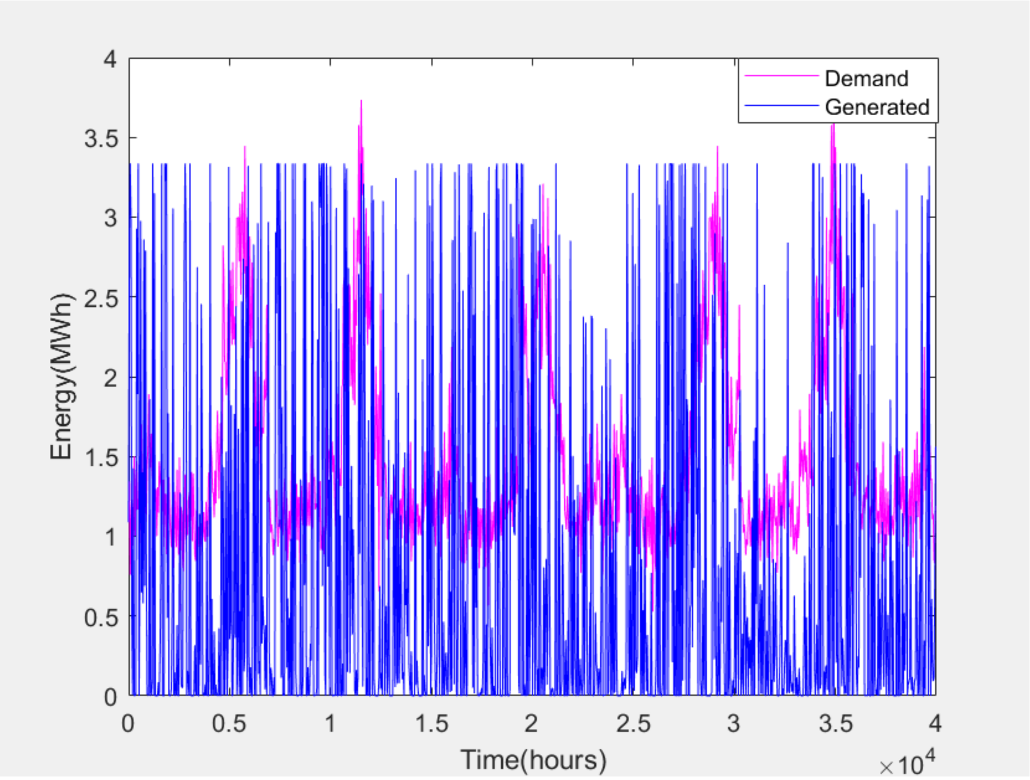
GRAPH 5: WIND SPEED SIMULATION FOR 10.000 HOURS

ENERGY GENERATION

Due to high variability of the wind, the wind park will either operate for long periods at maximum intensity, thus exceeding the energy demand, or even produce any energy at all (for low or extremely high wind velocities). It is therefore concluded that in parts of the non-interconnected high-wind network, in order to make wind energy sustainable, it is necessary to have the energy storage capacity.

In the case of Ikaria, the Wind Energy's Capacity Factor (CF) is estimated at 27.60%. The estimation of the Capacity Factor is made through running an hourly simulation for the seven years of the historical data and calculating the total energy generated throughout these years. Then, the Capacity Factor equals to the ratio of the aforementioned sum of produced energy and the installed power of the wind park multiplied by the total hours of simulation.

However, it is clear from the simulation of the operation of the wind farm (Graph 6) that only 62% of this energy would be exploitable without the parallel operation of the pumping system, while 2.685 MWh of surplus energy per year would be lost.



GRAPH 6: SIMULATION OF WIND PARK OPERATION

SYNTHETIC DATA

Hydrometeorological time series can be considered the cornerstone of any water-related engineering study, although, such data are in scarcity and often the available records don't have sufficient length for the task at hand (e.g., reliability and risk-related studies). Historical records of such observations will rarely if ever repeat in the future, which is the simplest manifestation of the high variability and uncertainty that is naturally inherited therein. In this vein, it can be argued that embracing stochasticity in hydrometeorological processes is a first step towards the development of uncertainty-aware methodologies for water systems. Stochastic simulation, and the synthesis of long hydrometeorological time series, which are used in place of historical ones, can provide a potential remedy to this situation. Synthetic time series are not predictions of future states, but rather constitute plausible realizations of the simulated process, that are, loosely speaking, statistically equivalent with the parent information (i.e., historical data). Driving the typically deterministic water-system simulation models with such realizations provides the means to assess their response in a probabilistic manner, under multiple, plausible scenarios (Tsoukalas *et al.*, 2018b).

MARKOV MODEL

Due to the intrinsically uncertain nature of meteorological phenomena and the limited lengths of the historical data, it is essential to employ stochastic approaches to represent the above non-deterministic inputs. Firstly, a first class Markov model was developed in order to provide sufficiently large samples, in order to evaluate the system responses in statistical terms (e.g., by means of reliability), with satisfactory accuracy.

The Markov model is described by the following equation:

$$X_{\mathrm{i}} = r \times X_{\mathrm{i-1}} + w_{\mathrm{i}} \qquad \text{Eq. (8)}$$

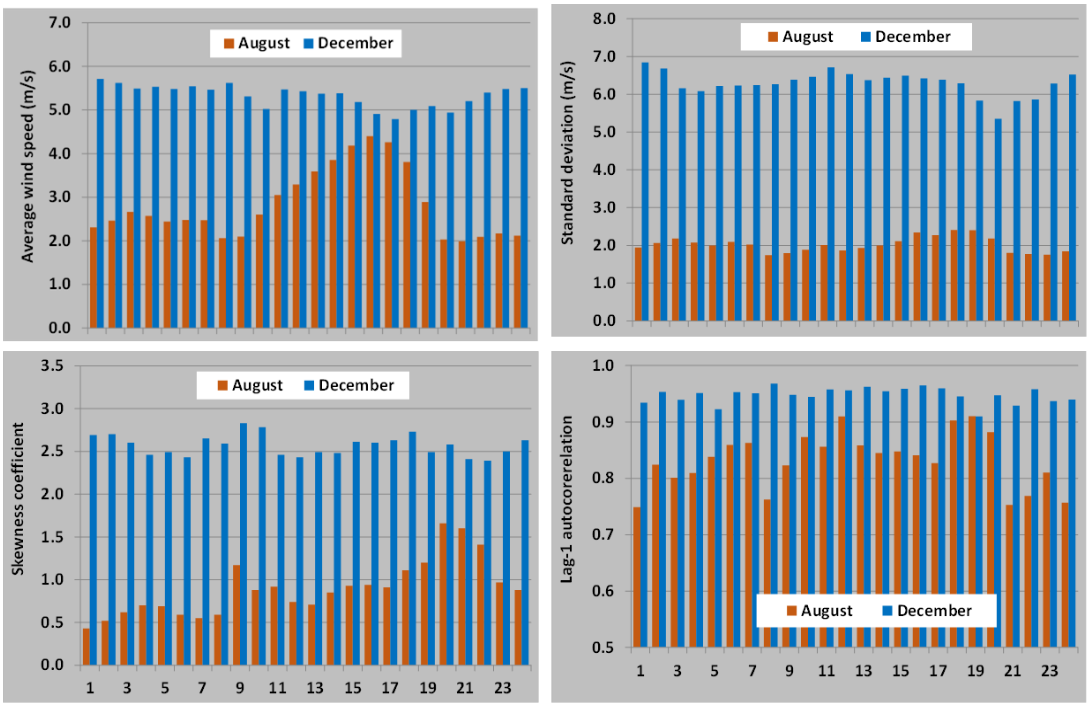
The autocorrelation of the historical wind speed data is considered as r, while w_i represents white noise of mean value equal to the mean value of the historical data multiplied by $(1 - r)$ and variance equal to the one of the historical data, multiplied by $(1 - r^2)$. Therefore, the value of wind speed in each step is defined to some extent by the value of the previous step and by the varying white noise.

SPARTA MODEL

The wind speed process at fine time scales (e.g. hourly) is characterized by major peculiarities, since its statistical behavior changes both across seasons and the daily cycle (an attribute referred to as double periodicity; cf. Dimitriadis & Koutsoyiannis, 2015). Statistical analysis of hourly wind data from Ikaria (2012-2018) also revealed the existence of intermittency, large asymmetry and strong auto-dependence across short time scales.

In Graph 7, plots of intra-daily (hourly) statistical characteristics of wind speed at Ikaria, for two characteristics months (December, August) are presented.

The historical data are used as input to a novel stochastic modelling approach, named Stochastic Periodic Auto-Regressive to Anything (SPARTA), for generating 1.000 years of hourly synthetic data, to be used within water-energy simulations (Tsoukalas *et al.*, 2018a, b; Tsoukalas, 2018).



GRAPH 7: STATISTICAL CHARACTERISTICS OF THE SAMPLE OF WIND SPEED FOR DECEMBER AND AUGUST

Main advantages of SPARTA are the preservation of double periodicity (cyclostationarity), by allowing fitting to any distribution model to represent the individual statistical regime of each hour of each month, and the generation of realistic dependency patterns. To describe the intermittent nature of the wind, mixed-type distributions with Generalized Gamma and Burr type-XII were used for representing non-zero wind speed.

Using the synthetic time series, the Wind Energy's Capacity Factor (CF) is estimated at 26.30%. Firstly, an hourly simulation for the 1.000 years of the synthetic data is being processed and the total energy generation is calculated. Then, the Capacity Factor equals to the ratio of the sum of produced energy and the installed power of the wind park multiplied by the 8.760.000 hours of simulation. About 63,8% of the energy production enters the grid as soon as it generated, while the energy excess is approximately 2.523 MWh/year.

The mean value of the wind speed of the hourly synthetic data at the measured altitude is calculated at 5,32 m/s and its standard deviation 7,63 m/s. As shown in Graph 8, generally the wind speed in December is way higher than in August. This is confirmed by the statistical characteristics of the synthetic data, as the mean value of wind speed in August is 2,9 m/s and in December 5,8 m/s. The fact that the synthetic data reproduces the monthly fluctuations of wind speed shows that the stochastic model itself has the ability to represent cyclostationarity.

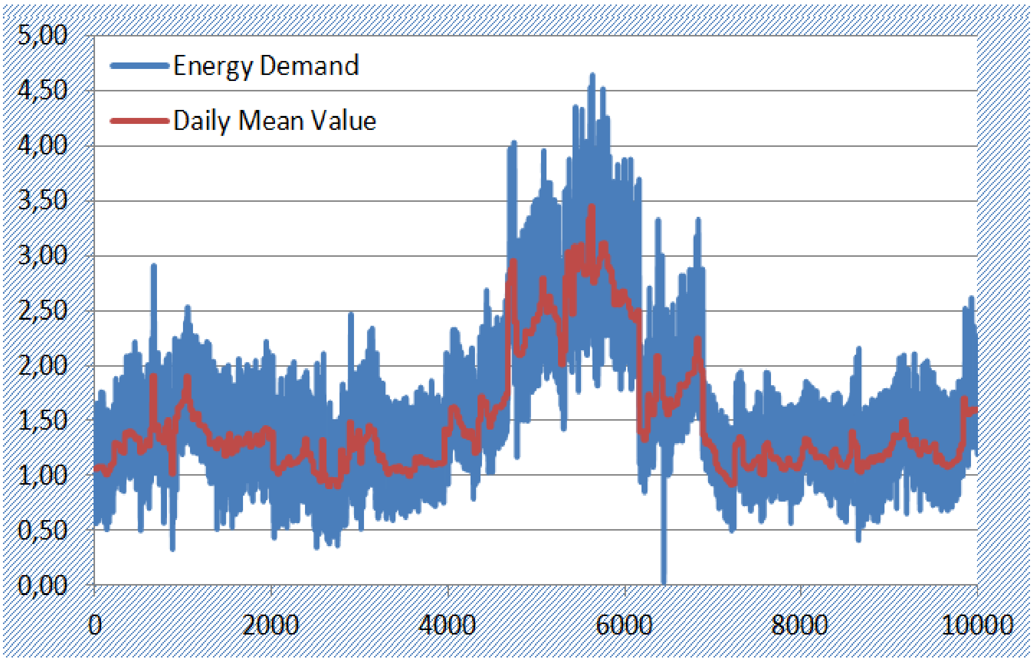
ENERGY DEMAND DATA

The energy demand data across the Island of Ikaria could not be found for the purposes of this thesis. Thus, data from the neighboring island of Astypalaia was used (Chalakatevaki *et al.*, 2017), to which we employed a proportional adjustment based on the ratio of the populations of the two islands (8400/2000). The island's average power demand is 1.60 MW.

Ikaria, as being an island receiving tourist flows, shows a significant increase in average demand for energy during the summer period. An additional parameter that hinders the hybrid system's effort to achieve high reliability is that during the summer period, the operating rules do not allow the use of the Proesperas' hydroelectric power plant to meet energy deficits, due to increased irrigation demand. Because of these two constraints, it is concluded that the majority of the energy deficits will occur during the summer period.

Another pattern observed in the energy demand profile of the island is its decrease during the weekend. It is a pattern that is also observed in parts of the continental network and is related to the carrying out of a different type of activity by the human factor.

Graph 8 illustrates a simulation of energy demand in Ikaria Island for 10.000 hours.



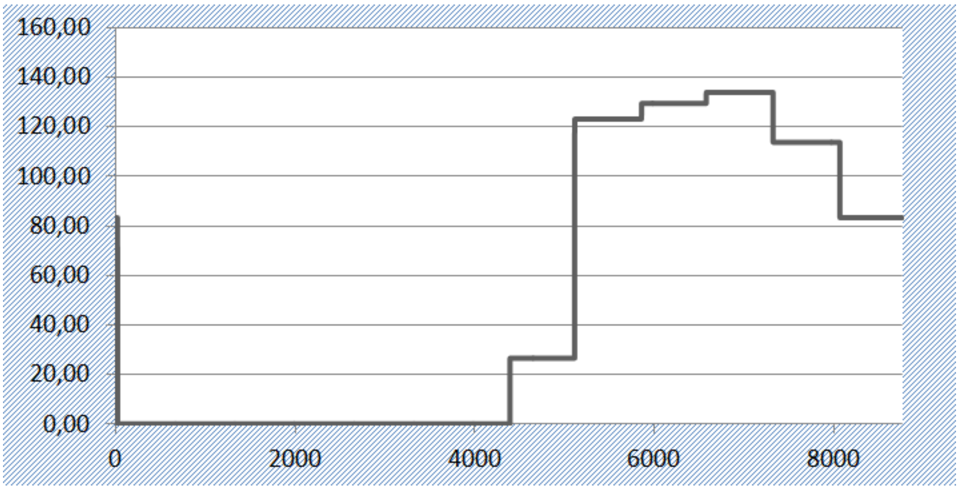
GRAPH 8: ENERGY DEMAND SIMULATION FOR 10.000 HOURS

IRRIGATION DEMAND DATA

Pezi Dam offers about 448.000 m^3/year to meet the irrigation needs, which accounts for 80% of the total demand of the island. The remaining 20% is fulfilled by local drilling.

The irrigation demand profile shows a drastic difference between summer and winter. More specifically, from October to March, demand is just over 3 m^3/day. The months of April and September could be described as transient for the passage from winter to summer and vice versa. On the other hand, from May to August the daiy demand exceeds 3.000 m^3, thus justifying the priority of the irrigation use during the summer season.

Graph 9 shows a simulation of irrigation demand on Ikaria for 8.760 hours.



GRAPH 9: IRRIGATION DEMAND SIMULATION FOR ONE YEAR

CHAPTER 5: SIMULATION MODEL

FIXED DESIGN CHARACTERISTICS

The hybrid energy system project is being built in the former municipality of Raches. Its current design includes the wind farm in the Stravokoundoura hill area, consisting of three Enercon E-44/900 wind turbines, a 600 kW wind turbine in Perdiki, the Kato Proespera pumping station, consisting of 12 pumps (4 of them spare) of total nominal power 3 MW, two tanks, and the Pezi reservoir. Their locations across the island are shown in Figure 31. As described in Chapter 3, the reservoir has of a useful storage capacity of 910.000 m^3 and is connected with the two tanks in Proespera and Kato Proespera, respectively, with a storage capacity of about 80.000 m^3, to serve the needs of pumping for the absorption of wind energy. The hybrid scheme also includes the Proespera Small Hydroelectric Plant with a 1,05 MW Pelton-type hydro-turbine, which will only utilize the excess water of Pezi reservoir, and the Kato Proespera Plant, with two hydro turbines of Pelton type, with a power capacity of 2×1,55 MW, which will exploit both the excess water of the reservoir and the water obtained through pumping.

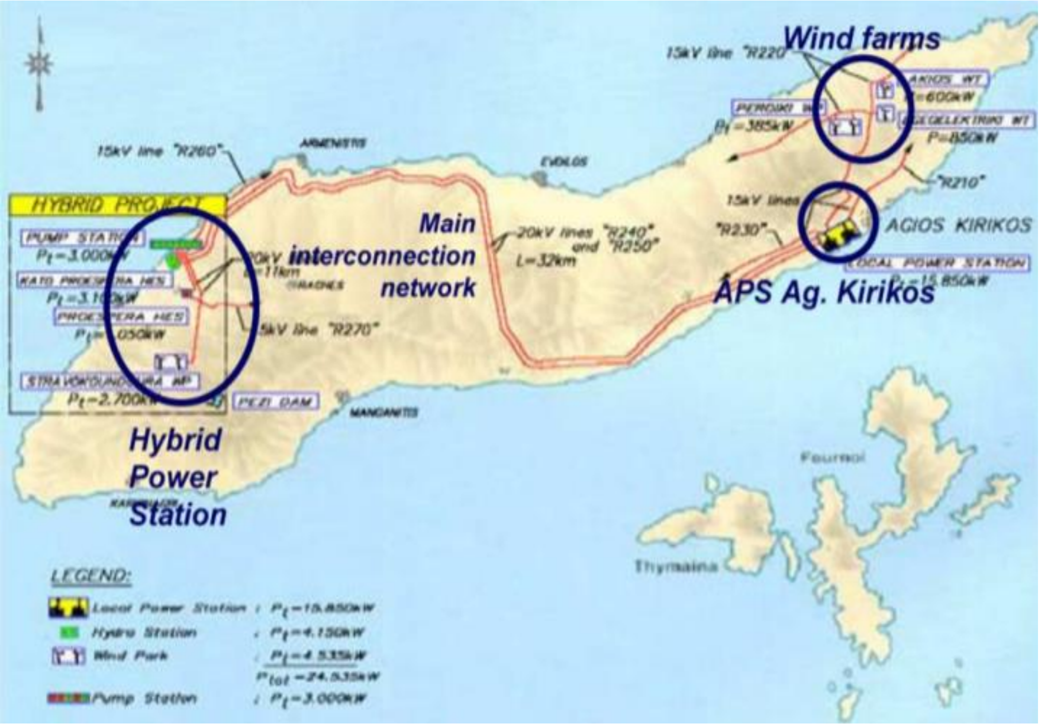


FIGURE 31: LOCATION OF HPS AND OTHER POWER STATIONS' (PAPAEFTHYMIOU, 2012)

The first step in simulating the hybrid energy system is to represent the hydraulic quantities that govern the system, in order to capture the parallel operation of wind farm and pumping station.

As already mentioned, the useful capacity of the reservoir in Pezi amounts to 910.000 m^3, with maximum operating elevation at +721 m and minimum operating elevation at +695 m. Knowing the match of level, z, and storage, S, easily results in the equation that characterizes the morphology of the reservoir:

$$S = 147.7\, z^{2.68} \qquad \text{Eq. (9)}$$

Given this equation, it is concluded that the reservoir at low altitudes is much "narrower" than at the highest. This is confirmed by the fact that at the upper one meter of the reservoir level, 9% of the reservoir's storage is enclosed.

The two tanks in Proespera and Kato Proespera have exploitable volume of water of about 80,000 m^3 and are expected to be used mainly for pumped storage. The maximum operating altitude of the upper tank is +554m, while the lowest is at +543 m (tank height 11 m). Correspondingly, the lower tank has height of 12 m, with a maximum operating level of +50 m and a minimum of +38 m. Both tanks are considered, approximately, rectangular.

The sum of the reservoir and upper tank storage basically expresses the stored energy of the hydro pumped storage system. Summing up their maximum energy stocks multiplied by an average altitude from the lower tank and using the following equation:

$$E = \eta\, \gamma\, H_n \int Q(t)\, dt = \eta\, \gamma\, V\, H_n \qquad \text{Eq. (10)}$$

By applying eq. (10) for the maximum storage of the upper tank and the reservoir and an average altitude difference, we get that the pumped storage system can ensure a maximum energy production of 1592 MWh. Obviously, the amount of energy that can be produced at any time is determined by the completeness of the upper tank and the reservoir, and also by the maximum capacity of the grid, hence the nominal power of the hydro turbines.

The maximum flow capacity of the two cycles (reservoir-upper tank, upper tank-lower tank) is calculated on the basis of the nominal power of the two hydro turbines, the average altitude difference between the reservoirs' water levels and the turbine efficiency, which equals 0,90. For the first route the maximum capacity is estimated at 2.564 m^3/h, while between the two tanks is 2.508 m^3/h. Nevertheless, the most critical binding factor of the system is the minimum discharge with which the Pelton hydro turbine can produce hydro power, which is equal to 0,13 Q_D = 340 m^3/h. This quantity drastically affects the overall performance of the system, because in its simulation, there are not only a few cases in which the system operator is forced to release that quantity to operate the hydroelectric turbine to encounter lower energy deficits. As a result, water releases that could be used to cover future energy and irrigation deficits are reduced to lower altitudes, resulting in a reduction in overall system performance.

Two factors that also significantly influence the results of the simulation model are linear (friction) and local hydraulic losses.

Determining the magnitude of linear hydraulic losses (h_f) generally depends on the following pipe dimensions:

- Length (L);
- Diameter (D);
- Equivalent roughness;
- Discharge (Q);
- Energy gradient (J).

The length of the pipes between the reservoirs are the following: from Pezi Dam to the Ano Proespera tank the pipeline length is 3.500 m, from there to Kato Proespera tank is 3.060 m, while at the reverse direction the associated length is 3.100 m.

The diameter is varying across the different routes. Note that because in the middle of route reservoir-upper tank (1-2), the diameter of the inlet duct changes from 0,80 m, at 0,70 m, the paths 1-1.5 and 1.5-2 were also considered to indicate this change. The diameter along the 2-3 route is 0,60 m, while along the lower tank-upper tank route is 0,50 m.

The estimation of the equivalent roughness, *ε*, is subject to several uncertain factors, related with the pipe material and age, the water quality characteristics, etc. According to typical design practices, we used a value of 1 mm.

Koutsoyiannis (2008) introduced the so-called generalized Manning equation, to approximate the complex friction factor of the Colebrook-White equation through an analytical (closed) equation. The proposed procedure uses three parameters (*β*, *γ*, *N*), which are estimated as follows:

$$\beta = 0.25 + 0.0006\,\varepsilon_* + \frac{0.024}{1 + 7.2\,\varepsilon_*} \quad \gamma = \frac{0.083}{1 + 0.42\,\varepsilon_*} \quad N = 0.00757\,(1 + 2.47\,\varepsilon_*)^{0.14} \qquad \text{Eq. (11)}$$

where $\varepsilon_* := \varepsilon/\varepsilon_0$ is a dimensionless roughness and $\varepsilon_0 = 0.05$ mm. The above parameters are considered constant, provided that the flow velocity ranges between 0,3 and 10,0 m/s. For given *β*, *γ*, and *N*, the energy gradient, *J*, is determined by:

$$J = \left(\frac{4^{3+\beta} N^2 Q^2}{\pi^2 D^{5+\beta}} \right)^{1/(1+\gamma)} \qquad \text{Eq. (12)}$$

The value of linear losses is calculated as the product of energy gradient and the length. Therefore, the linear losses value is expected to vary in every hourly step.

The mean value of the 1-2 route is approximately 7 m and the one of the 2-3 route is about 12 m. Nevertheless, the exact value is explicitly calculated in every step of the simulation procedure.

The local hydraulic losses are determined at each step on the basis of flow velocity. The fixed factor of local hydraulic losses is considered at a very conservative value. Therefore, the mean value of local losses in each step is calculated at 0,90 m, which is a value significantly lower than the one of the linear hydraulic losses.

Regarding the wind energy generation, at each hourly step the wind speed at the measured height is adjusted to the height of the turbines (i.e. the height of the hub), using the adjusting coefficient. Next, using the power curve of the wind turbines, the generated power of the wind farm is calculated at every simulated hour.

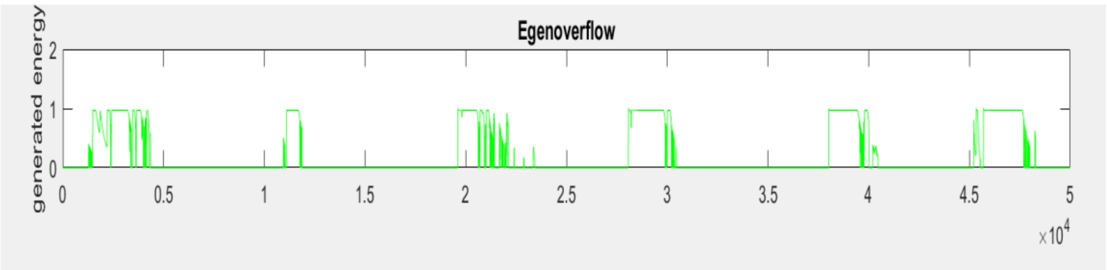
HYBRID ENERGY SYSTEM’S OPERATION

The simulation of the operation of the hybrid energy system, without the contribution of the autonomous power system, was developed in Matlab®. The code runs a simulation of 45 years using an hourly time step. For the operation of the system two possible scenarios were examined: one featuring unlimited pumped storage between the reservoir and the tanks, and one with seasonal restrictions due to the prioritization of the irrigation demand.

The simulation consists of many phases which resemble the different operation options of the hybrid system.

First of all, at each time step the capacity of each route is calculated on the basis of the nominal power of the two hydro turbines, the distance between the reservoirs and the turbine efficiency. This value defines the maximum possible transport of water between the tanks and the differentiation of the results of the system will be examined during the optimization of the system.

Following, the reservoir spill takes place. In each step, the estimated runoff is added to the existing reservoir storage. If the resulting storage is greater than the maximum capacity of the reservoir, water is driven down to the upper tank in order to generate energy. First, the energy gradient, *J*, is calculated as a result of the flow and roughness, to define the linear hydraulic losses. In addition, the speed of the water flow determines the value of the local hydraulic losses. Consequently, the value of the outflow, which always is less than the maximum capacity of the reservoir-upper tank route, is transferred to the upper tank through the Ano Proespera hydroelectric plant. If the transferred water is less than the minimum flow with which the Pelton hydro turbine can produce hydropower, no power is generated. At the end, the storage of the reservoir equals its net volume and the transferred amount of water is added in the existing storage of the upper reservoir. The altitude of the water level of both the reservoir is calculated using eq. (9). The mean generated power due to spill of the reservoir equals to 0,52 MWh and spill occurs approximately 35% of the simulation hours, mostly in the winter season. The produced power is used to cover deficits of the energy demand. As shown in Graph 10, the energy generation due to spill takes place mostly in winter season.



GRAPH 10: ENERGY SIMULATION FROM RESERVOIR SPILL SIMULATED FOR 50.000 HOURS

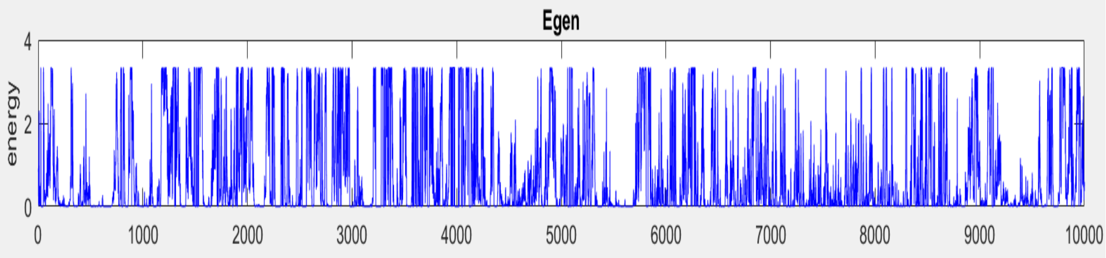
Next, abstractions for irrigation take place. The irrigation demand profile shows a significant difference between summer and winter season: from a mean value of 3.000 m^3/day to 3 m^3/day. Hence, the transfer of water to meet the requirements of irrigation will mainly occur in the summer months.

First, it is examined whether it is possible to cover the irrigation needs using the existing reservoir resources. If so, then any failure occurs and any energy is required to cover the irrigation demand. If not, and in case that water can be pumped into the reservoir (will be examined later), then water from the upper and, if needed, also the lower tank, is transferred to the reservoir, provided that it does not exceed the maximum capacity of the pumping station. Therefore, we calculate the linear and local hydraulic losses and the required power to pump the water into the reservoir. This amount is added to the existing energy demand of the island. The mean value of this additional power target is minor, as this case occurs less than 0,5% of time.

If the irrigation demand exceeds the cumulative storage of the reservoir and the two tanks, failure occurs regarding the irrigation needs of the island. A counter is used in order to account for the time steps in which the system is not able to cover the irrigation demand and by dividing it with the total hourly steps in which there was need for irrigation, the percentage of system failure accrues. Simultaneously, an adder concentrates the total amount of water that the system was short of. By dividing it with the failure counter, the vulnerability of the irrigation system is calculated. Last but not least, the resilience resembles the maximum consecutive times during which failure occurred out of the total times of failure.

Following, the wind farm energy generation is simulated. The hourly wind speed data is used as input to the power curve (Figure 26), in order to define the amount of energy production. The generation of energy from the Stravokoundoura wind farm is the result of the individual wind turbine, multiplied by the number of the wind turbines (three). On the other hand, for the standalone Perdiki wind turbine of 600 kW, the former result is multiplied by (600/900), which is the ratio of nominal capacities of the two turbines.

Based on the above assumptions, we run the hourly simulation model and estimated the energy produced by the system. Its mean value is 0,82 MWh and its standard deviation is 1,15 MWh. In Graph 11, 10.000 hours of simulated energy generation are shown. We remark that the total installed power of 3,3 MW imposes an upper limit to the energy generation. Furthermore, almost 25% of the total simulation hours no energy was produced.

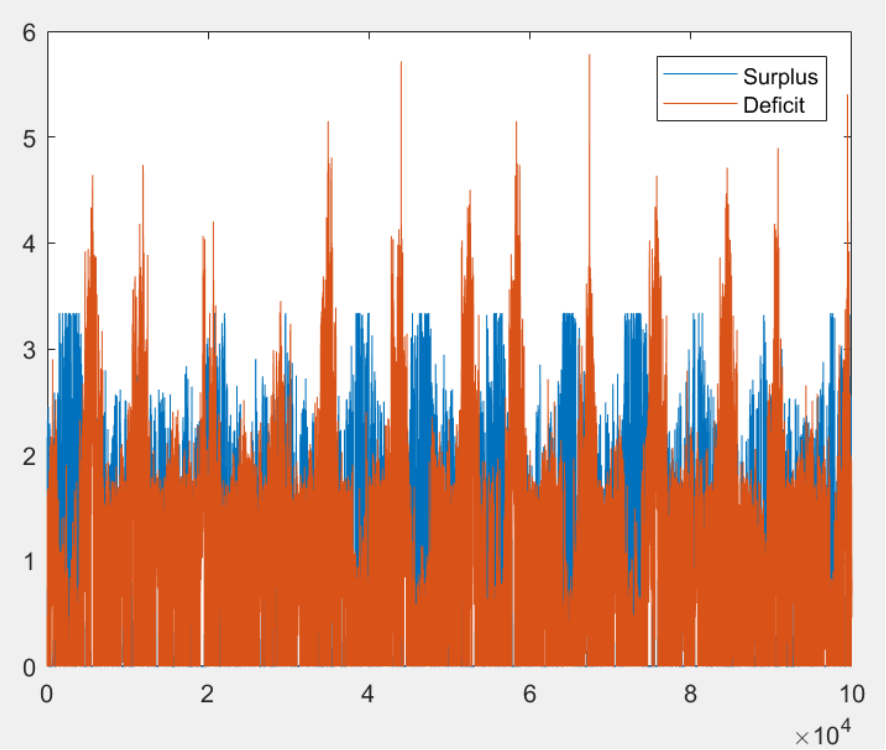


GRAPH 11: ENERGY GENERATION SIMULATION FOR 10.000 HOURS

As a result, whenever the sum of the energy generated from the wind parks and the spill of the reservoir is greater than the energy demand of the island, surplus occurs and there is a chance for pumped storage. Otherwise, the deficit is encountered by the generation of energy using either the Ano Proespera or Proespera hydroelectric plant. By the simulation of the hybrid system is shown that deficits occur approximately 74,30% of the simulation hours with a mean value of 1,23 MWh, while the average surplus is 1,41 MWh. In Graph 12, a simulation of 100.000 hours of the hybrid system presents the hourly deficits and surpluses of energy.

Next, the water level of the reservoir is calculated using eq. (9). Moreover, the water level of the two tanks is defined. In addition to this, the completeness of the reservoir and the tanks is defined as a ratio between its storage and its capacity.

Afterwards, if deficit occurs we enable the operation of the turbines. The selection of either the reservoir-upper tank route or the upper tank-lower tank one is based on multiple factors. The key one is the completeness of the reservoir and the tank, also accounting for the seasonal restrictions. In particular, during the summer months, due to the increased irrigation needs, the completeness of the reservoir is relatively low. As a result, regardless of the implementation or not of seasonal restrictions setting irrigation as a priority, the energy generation through the upper tank-lower tank route is mostly selected. Nevertheless, the overall goal is to preserve the reservoir storage, in order to be used both for irrigation and energy production.



GRAPH 12: SIMULATION OF SURPLUSES AND DEFICITS FOR 100.000 HOURS

If the reservoir-upper tank route is selected for energy generation, firstly the discharge is calculated using the following equation:

$$Q = Def./(Tur.eff. \times 9.81 \times (Hres - Hupper)) \qquad \text{Eq. (13)}$$

where the energy deficit is expressed in kWh and the turbine efficiency is set equal to 0,90.

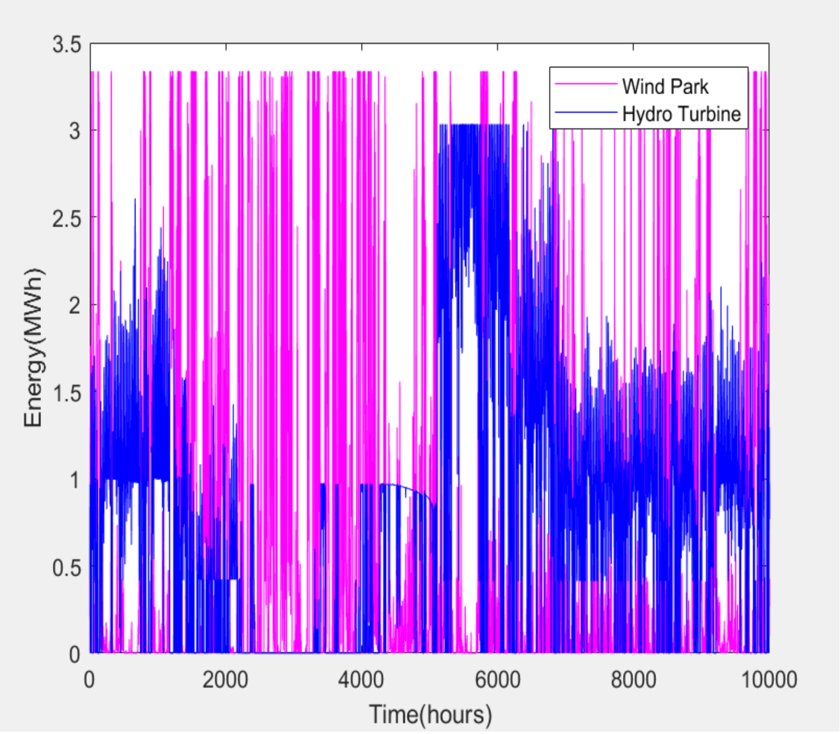
The discharge should not exceed the maximum reservoir-upper tank's capacity and the existing storage of the reservoir. Concurrently, the discharge should be high enough so that the turbine has the ability to operate. In case of small-scale deficits and due to the existence of the minimum discharge with which the Pelton turbine can produce hydropower, larger amounts of water have to be released, and as a result more water is transported to lower levels. Therefore, during the optimization of the system, the influence of this quantity in the reliability of the system will be examined.

Next, by applying eq. (12) and after calculating the flow velocity, linear and local hydraulic losses are defined. Given that, using eq. (13) we calculate the total amount of water to be released in order to generate energy equal to the deficit. This amount cannot exceed the existing storage and the maximum capacity of the turbines.

A counter is used in order to account for the time steps during which the system is not able to cover the energy demand, and by dividing it with the total number of hourly steps we get the failure probability of the system. Moreover, an adder is used to concentrate the total amount of energy that the system was short of and by dividing it with the failure counter, the vulnerability of energy is calculated. Finally, the resilience resembles the maximum consecutive times in which failure occurred out of the total times of failure.

When the amount of released water is less than the minimum necessary amount for turbine operation, then failure occurs and no energy is generated. As a result, the failure counter is increased by one and the whole amount of deficit is added to the energy failure sum. If the available storage or capacity of the turbines limit the energy generation in quantities less than the existing deficit, then the generated energy is injected to the energy grid, but still failure occurs. Hence, the failure counter is increased by one and the deficit minus the amount of energy generation is added to the energy failure sum.

Next, the total amount of energy generation is calculated using eq. (10). A simulation of energy generated from the wind park and the turbines for 100.000 hours is presented in Graph 13.



GRAPH 13: SIMULATION OF ENERGY GENERATION OF WIND PARK AND HYDRO POWER PLANTS FOR 100.000 HOURS

Following, the transported amount of water is removed from the previous reservoir storage and, concurrently, is added to the storage of the upper tank.

If the upper tank-lower tank route is selected, the procedure is almost the same.

Initially, the discharge is calculated using eq. (13), based on the elevation difference between the upper and lower tank. As before, the discharge cannot exceed the maximum capacity of the selected route and the existing storage of the upper tank, while it should be higher than the minimum discharge of the Pelton turbine.

Next, since the value of the hydraulic losses is defined, the total amount of water that should be released into the turbine in order to generate energy equal to the deficit is calculated, which does not exceed the existing storage of the upper tank and the maximum capacity.

Next, if the amount of transported water is less than the minimum necessary amount for the turbine to operate, then the failure counter is increased by one and the whole amount of deficit is added to the energy failure sum. In case that the generated energy is less that the deficit, the failure counter is increased by one and the deficit minus the amount of energy generation is added to the energy failure.

Then, the total amount of energy generation is calculated by eq. (10), the released amount of water is removed from the upper tank and is added to the lower one.

Nevertheless, in case that surplus occurs the procedure continues by pumping water into higher levels. The results of the system are examined using two different models: one with the ability only to pump water from the lower to the upper tank, and one with the ability to pump water through both of the routes, i.e., lower tank-upper tank and upper tank-reservoir. The decisive factor for selecting the route of the pumping water is, firstly, the completeness of the reservoir and, secondly, the completeness of the two tanks, because the main goal is that the storage of the reservoir should remain high. Specifically, the scenario of pumping water into the reservoir is selected in case that the completeness of the upper tank is higher than a standard value or the completeness of the reservoir is lower than a critical value (which may change during different seasons) and the upper tank has water to give. If none of these criteria is satisfied, then the water is pumped from the lower to the upper tank.

In case that the upper tank-reservoir route is selected, the discharge is calculated using the following equation:

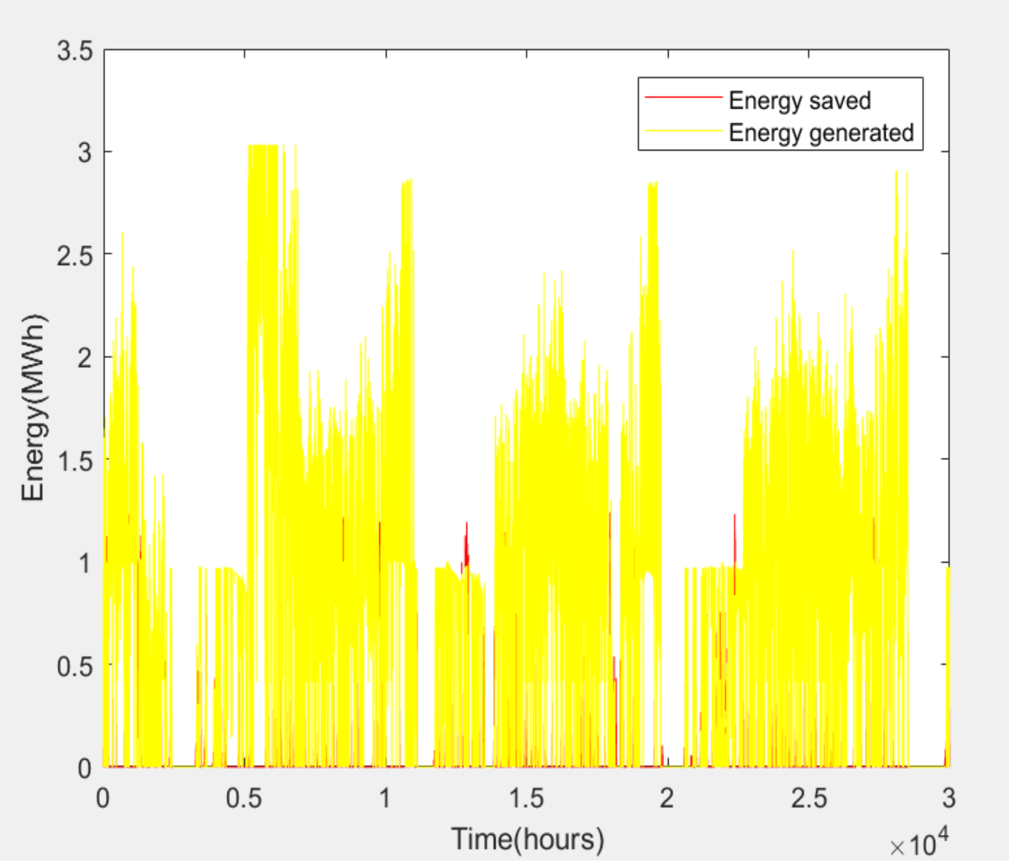
$$Q = Sur \times Pumpeff/(9.81 \times (Hres - Hupper)) \qquad \text{Eq. (14)}$$

where the energy surplus is represented in kWh and pump efficiency equals to 0,69. The discharge should not exceed the maximum upper tank-reservoir's capacity and the existing storage of the upper tank.

By applying eq. (12), linear and local hydraulic losses are defined and by using eq. (14) the total amount of water that can be pumped into higher levels is calculated.

This amount does not exceed the existing storage of the upper tank and the maximum capacity of the pumping station.

Next, the total amount of saved energy is calculated and the transported amount of water is removed from the upper tank storage and added to the storage of the reservoir. A simulation of energy generated from the hydro turbines and saved due to pumping for 30.000 hours is presented in the following graph:



GRAPH 14: SIMULATION OF GENERATED AND SAVED ENERGY OF THE HYDRO PUMPED STORAGE SYSTEM FOR 30.000 HOURS

If the lower tank-upper tank route is selected, the discharge is calculated using eq. (14) and it should not exceed the maximum capacity of the pumping station and the existing storage of the lower tank.

After calculating the energy gradient and the flow velocity, linear and local hydraulic losses are estimated by using eq. (10) the total amount of water that can be pumped into the upper tank is computed. This amount should not exceed the existing storage of the lower tank and the maximum capacity of the pumping station. Following, the total amount of stored energy is calculated and the transported amount of water is removed from the lower tank storage and added to the storage of the upper one. In Figure 32, a highlight during pumping to the upper tank is shown.

FIGURE 32: HIGHLIGHT DURING WATER PUMPING INTO THE ANO PROESPERA TANK

At the end of each step, three counters estimate the time steps in which the reservoir and the two tanks are empty. After that, the counters are divided by the total number of simulation hours in order to express the percentage of times that either the reservoir or the tanks have no storage during the simulation.

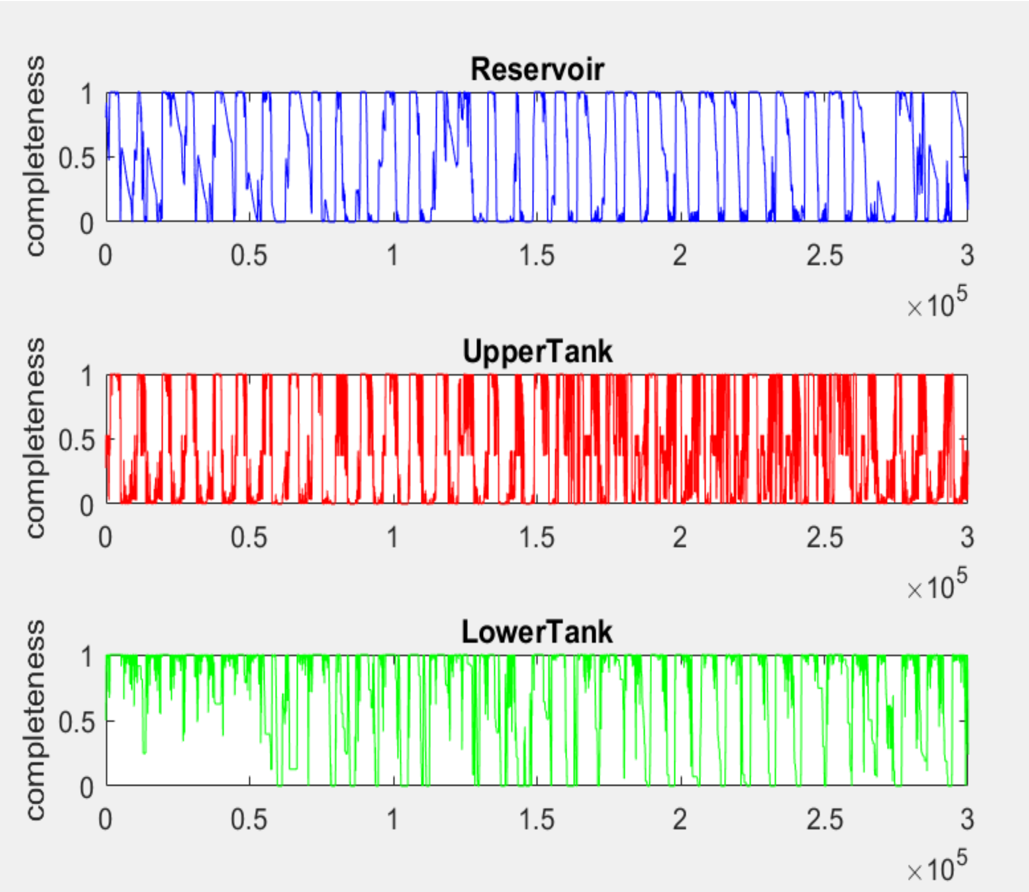
In addition, at the end of the simulation the following quantities are computed:

- irrigation failure, as the ratio of the counter of irrigation failure to the total hours of simulation;
- irrigation resilience, as the ratio of the maximum times of consecutive irrigation failure to the counter of irrigation failure;
- irrigation vulnerability, as the ratio of the sum of the total amount of water that the irrigation system was short of to the number of irrigation failures;
- energy failure, as the ration of the counter of energy demand failure to the total hours of simulation;
- energy resilience, as the ratio of the maximum times of consecutive energy demand failure to the counter of energy failure;
- energy vulnerability, as the ratio of the sum of the total amount of energy that the energy grid was short of to the counter of energy demand failure;
- the percentage of time that the reservoir and the tanks are empty;
- the earnings of the wind park operator, using the existing “guaranteed price” pricing system, as described in Chapter 2;

- the earnings of the hydroelectric power plant and reservoir operator, using a guaranteed price for the generated energy and constant values regarding the earnings and penalties of irrigation.

The time series of completeness of the reservoir, the upper tank and the lower tank are presented in Graph 15 for the simulation of the hybrid system, using seasonal restrictions and enabling pumped storage from the upper tank to the reservoir.

To sum up, this process is about the internal function of the hybrid system excluding the use of the autonomous power station and the daily operation of the energy market. Nonetheless, the operation of the system takes into account that the two operators are in cooperation with each other. Certainly, this fact does not hold during the operation of the system with the function of energy auctions where the different energy players are in competition.



GRAPH 15: TIME SERIES OF STORAGE COMPLETENESS FOR A SIMULATION OF 300.000 HOURS

However, the management models of the hybrid system are differentiated on factors relating to the options, capabilities and seasonal restrictions of the system. These management models are presented and compared in the next chapter in an attempt to define the optimal one.

SIMULATION OF DIFFERENT OPERATION MODELS

So far, we described the hybrid system without the exploitation of the autonomous power station. By changing the operation rules, we get significantly dissimilar outcomes. Since the hydraulic design sizes are fixed, the most critical factors that define the alternative management policies at each step refer to the selection of the optimal routes either for power generation or for pumping.

First, the operation of the two hydroelectric stations is governed by obligations rising from the environmental terms of the project and aim ensuring the irrigation adequacy of the reservoir. Specifically, the Proespera Hydroelectric Plant is not allowed to operate during the summer season (May-September), while the rest of the minimum water level requirements are set in the reservoir, according to PPC SA. In addition to this, in order to allow the reservoir responding to its complex requirements, a scenario of minimum allowable volume was drawn up by the PPC for the duration of its energy operation that is in the period from October to April. Based on this, in the beginning of the winter period, the energy exploitation is allowed to commence once the reservoir has gathered at least 500.000 m^3 of inflows, i.e. almost 55% of its maximum storage. The operation policy does not allow leaving the reservoir with less water until December 31. Then, the minimum threshold develops linearly with the day until the end of March, when environmental terms impose a minimum level of +720,0 m, corresponding to a storage of 819.259 m^3. During April the level should be at least +720,5 m, corresponding to a storage of 862.730 m^3. Then, until April 14th, the level is maintained above +720,5 m, thus the minimum desirable storage remains constant. From April 15th this limit is linearly increasing, so that until the end of April the reservoir becomes is full, thus reaching its capacity (910.000 m^3) and the maximum operation level (+721,0 m). From this day and until the end of the irrigation period, the energy operation of the reservoir as well as the function of the Proespera Hydroelectric Plant, are interrupted.

The seasonal restrictions regarding the completeness of the reservoir play a major role on defining the route for energy generation. For example, setting irrigation in highest priority means that during the summer months the upper tank-lower tank route will be the only way to generate energy. Given that, for almost five months the maximum capacity of energy storage of the system drops from 1592 to only 97 MWh, almost 6,1% of total. This drastic change is due to the fact that the maximum capacity and the elevation of the tank are remarkably lower than the ones of the reservoir. This means that during the summer season the irrigation needs cause very often energy demand failures. Even between October and April, the need for maintaining a minimum storage sometimes leads to energy demand failures. On the other hand, letting the hybrid system operate without setting seasonal restrictions may improve the energy generation reliability, but it surely leads to higher irrigation failures. Given that the penalty for irrigation failure is much higher than the price for successful provision of water, disabling seasonal restrictions will have notable cost. In addition, the effect on local society, although cannot be measured, is remarkable.

Second, the impact of water pumping potential from the upper tank to the reservoir definitely plays a key role in the system performance. In case that there is no such potential, due to the application of seasonal restrictions the sole way for the reservoir to reach the allowable volume levels is through natural inflows. As a result, the reservoir storage has to be conserved and the only way to cover energy deficits is through the use of water from the upper tank, leading to lower energy storage and higher energy demand failure. On the contrary, pumping water to the reservoir helps the system operating better, by increasing the maximum energy storage capacity.

Third, the decisive values of reservoir and tank completeness, according which the decision for selecting the proper route for energy generation or water pumping is made, are crucial regarding the system results. Emphasis is given in keeping the reservoir storage as high as possible, but simultaneously exploiting the energy storage potential of the tanks.

The impacts of these factors on the system behavior and especially on its reliability will be examined and compared by employing simulations for four different management policies.

SIMULATION NO.1

Simulation No.1 does not impose seasonal restrictions for the reservoir abstractions, and also allows pumping water to the reservoir.

The criteria for deciding the most suitable route for energy generation are the following: if the completeness of the reservoir is higher than 40%, while the storage of the upper tank is lower than the one of the lower tank, or the completeness of the upper tank is below 5%, then the reservoir-upper tank route is selected, otherwise the upper tank-lower tank one is used. As a result, circa 39% of simulation time in which deficit occurs the reservoir-upper tank route is chosen, while 61% of the time energy is generated by releasing water from the upper tank.

Regarding pumping, if the completeness of the reservoir is below 30%, while the storage of the upper tank is greater than the lower one, or the completeness of the upper tank is above 40%, then the upper tank-reservoir route is selected for energy storage, otherwise the lower tank-upper tank route is used. Thereafter, out of the total simulation hours in which surplus of energy was produced, 58% of time water is pumped to the reservoir, while 42% to the upper tank.

The final results of the simulation were:

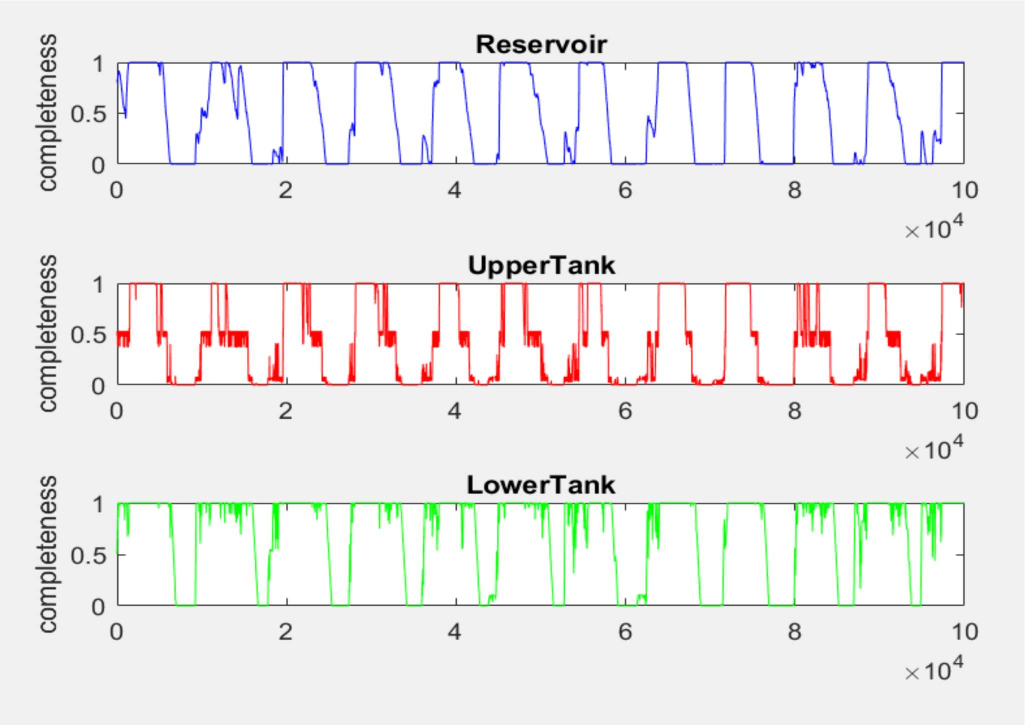
- Irrigation Reliability = 88,6%
- Irrigation Resilience = 0,003%
- Irrigation Vulnerability = 80,3 m^3
- Energy Generation Reliability = 59,0%
- Energy Generation Resilience = 0,001%
- Energy Generation Vulnerability = 1,12 MWh

In Graph 16, the time series of the storage completeness of the reservoir, the upper tank and the lower tank is presented. The reservoir is empty 25,4% of simulated hours, the upper tank 17,4% and the lower tank 13,3%.

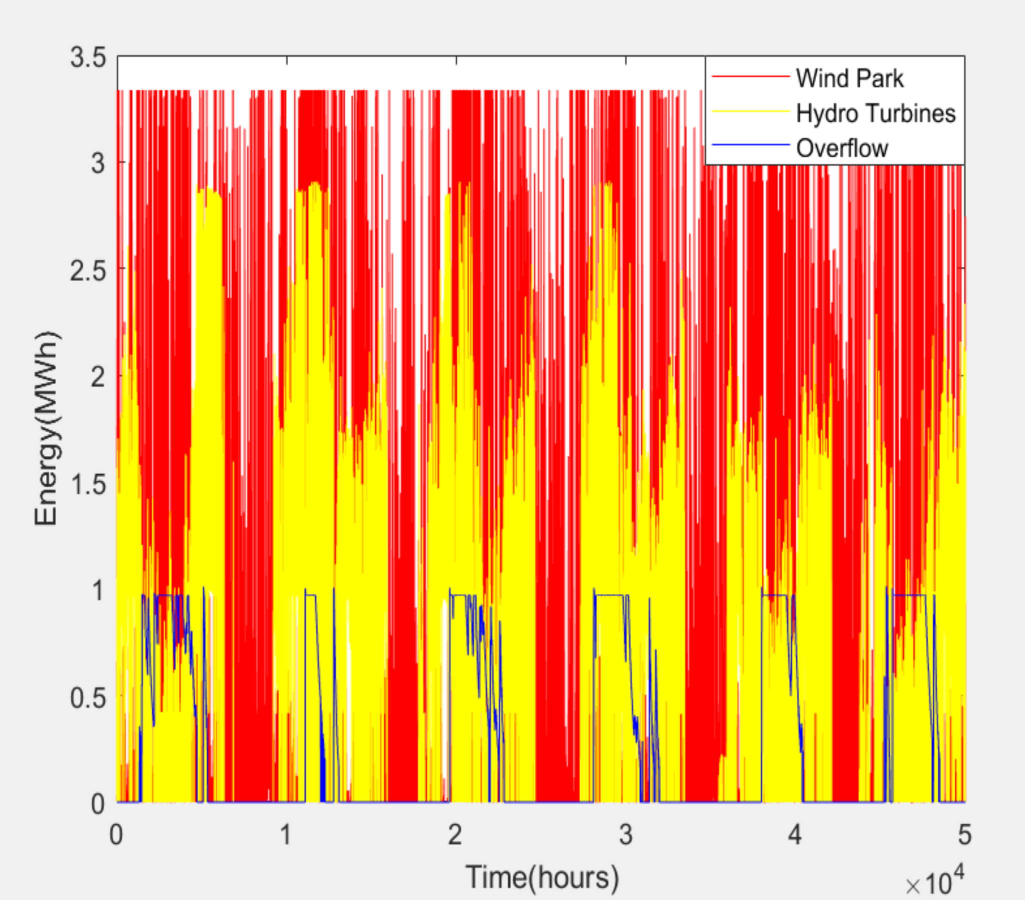
Regarding energy generation, the mean value of wind energy generation is 0,72 MWh with standard deviation 1,1 MWh. Concurrently, in 25,3% of the time steps energy was generated due to spill of the reservoir with mean value circa 0,78 MWh. Almost half of simulation period deficits are encountered through the operation of the turbines. The mean hourly energy generation is 1,0 MWh.

Graph 17 presents the distribution of simulated energy by different sources. As shown, half of generated energy arrives from the wind park, producing approximately 6,23 GWh/year, and half from the hydroelectric stations. 28% of this amount is produced from reservoir spill (1,73 GWh/year).

Using the “guaranteed price” model for wind energy pricing, which does not impose penalty for energy deficits, the simulation results to an approximate benefit of 527.000 €/year for the wind park operator. Simultaneously, according to RAE, the price set for the hydroelectric power plant is 295 €/MWh. So, the annual benefits of the operator are up to €1.475.000. Setting the irrigation price at 0,13 €/m^3 and its penalty at 1,04 €/m^3, the losses during the simulation are 1.612 €/year.



GRAPH 16: TIME SERIES OF STORAGE COMPLETENESS FOR SIMULATION NO.1



GRAPH 17: ENERGY GENERATION MIXTURE FOR SIMULATION NO.1

SIMULATION NO.2

Simulation No.2 accounts for seasonal restrictions, as defined by PPC SA, and also allows pumping water to the reservoir.

The criteria for deciding the proper route for energy generation are the following: between October and April, if the completeness of the reservoir is higher than the limit set by the seasonal restrictions, while the storage of the upper tank is lower than the one of the lower tank, or the completeness of the upper tank is below 5%, then the reservoir-upper tank route is selected for energy generation; otherwise the upper tank-lower tank route is used. Therefore, the reservoir-upper tank route is chosen about 34% of hours during which deficits occurred, while the rest of time energy was generated by releasing water from the upper tank.

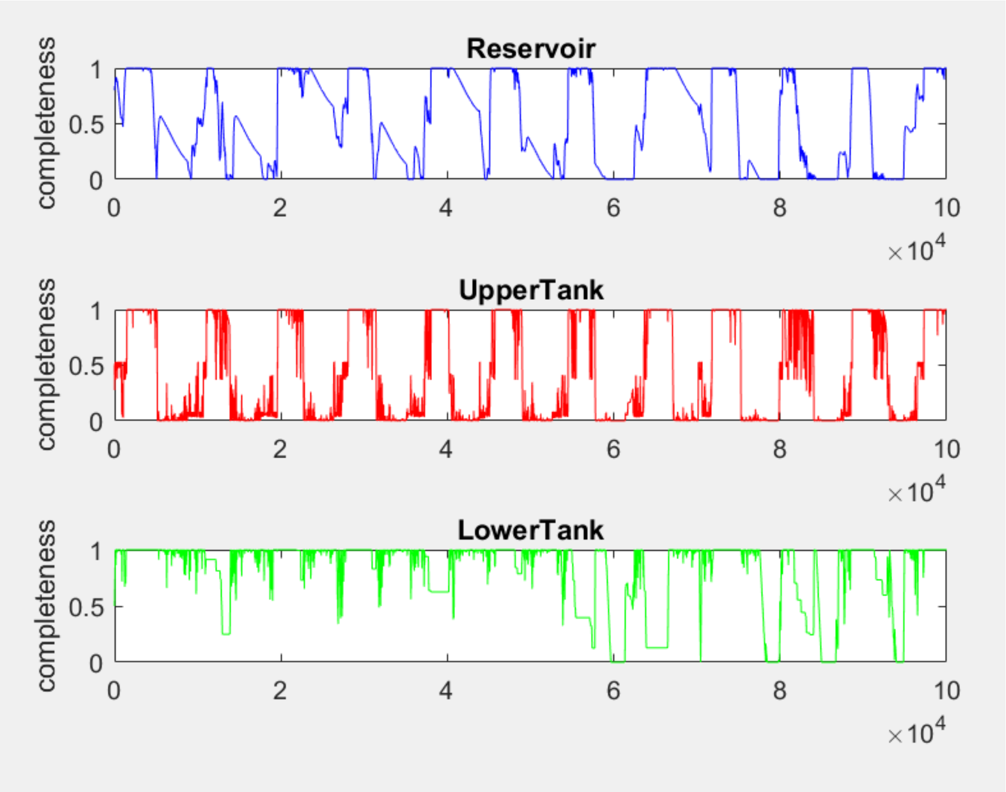
Regarding energy storage, if the completeness of the reservoir is below 20%, while the storage of the upper tank is greater than the one of the lower tank, or the completeness of the upper tank is above 40%, then the upper tank-reservoir route is selected for energy storage, otherwise the lower tank-upper tank one is used. Thereafter, 67% of the time water is pumped to the reservoir, while 33% of time it is pumped to the upper tank.

The final results of the simulation were:

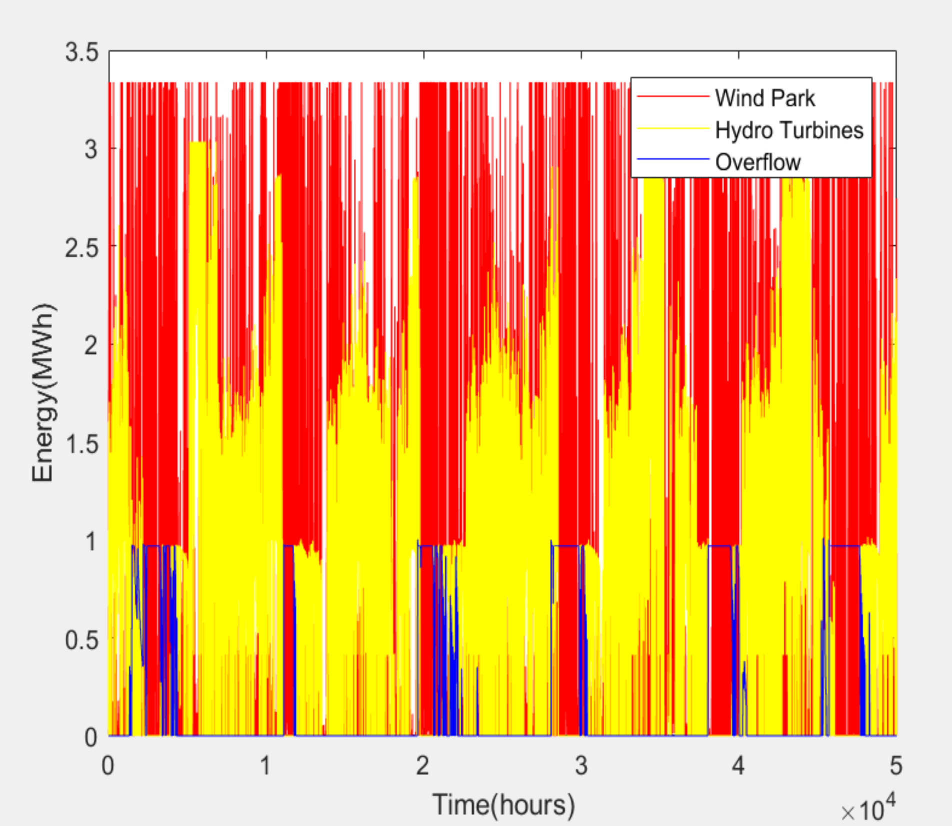
- Irrigation Reliability = 95,6%
- Irrigation Resilience = 0,008%
- Irrigation Vulnerability = 111,9 m^3
- Energy Generation Reliability = 61,0%
- Energy Generation Resilience = 0,001%
- Energy Generation Vulnerability = 0,88 MWh

Graph 18 presents the time series of storage completeness of the reservoir, the upper tank and the lower tank for 100.000 simulated hours. The reservoir is empty 15,0% of time, the upper tank 27,7% and the lower tank 11,1%.

Concurrently, the mean value of wind energy generation is 0,72 MWh, with standard deviation 1.1 MWh. In almost 22% of the simulated hours energy was generated due to spill of the reservoir, with mean value of 0,81 MWh. Approximately 57% of the hours of the simulation deficits are encountered through the turbine operation, which results to a mean hourly value of 1,12 MWh.



GRAPH 18: COURSE OF STORAGE COMPLETENESS FOR SIMULATION NO.2



GRAPH 19: ENERGY GENERATION MIXTURE FOR SIMULATION NO.2

Graph 19 presents the distribution of simulated energy by different sources. In particular, 46,8% of total annual energy generation (6,23 GWh) arrives from wind farms, 41,4% is directly produced from the hydroelectric stations (5,55 GWh) and the rest one is produced from reservoir spill (1,58 GWh). Thus, the wind park operator earns 527.000 €/year and the hydroelectric plant operator 1.637.545 €/year, using the same pricing policy as in simulation No.1. Setting the irrigation price at 0,13 €/m^3 and its penalty at 1,04 €/m^3, the associated benefits are 35.000 €/year.

SIMULATION NO.3

In Simulation No.3 no seasonal restrictions are set for the reservoir, while it is also not allowed pumping water to the reservoir.

The criteria set for deciding the proper route for energy generation are the following: if the completeness of the reservoir is higher than 60%, while the storage of the upper tank is lower than the lower one, or the completeness of the upper tank is below 5%, then the reservoir-upper tank route is selected for energy generation, otherwise the upper tank-lower tank one is used. As a result, circa 34% of simulated hours in which deficit occurred the reservoir-upper tank route is chosen, while the rest of time energy is generated by releasing water from the upper tank.

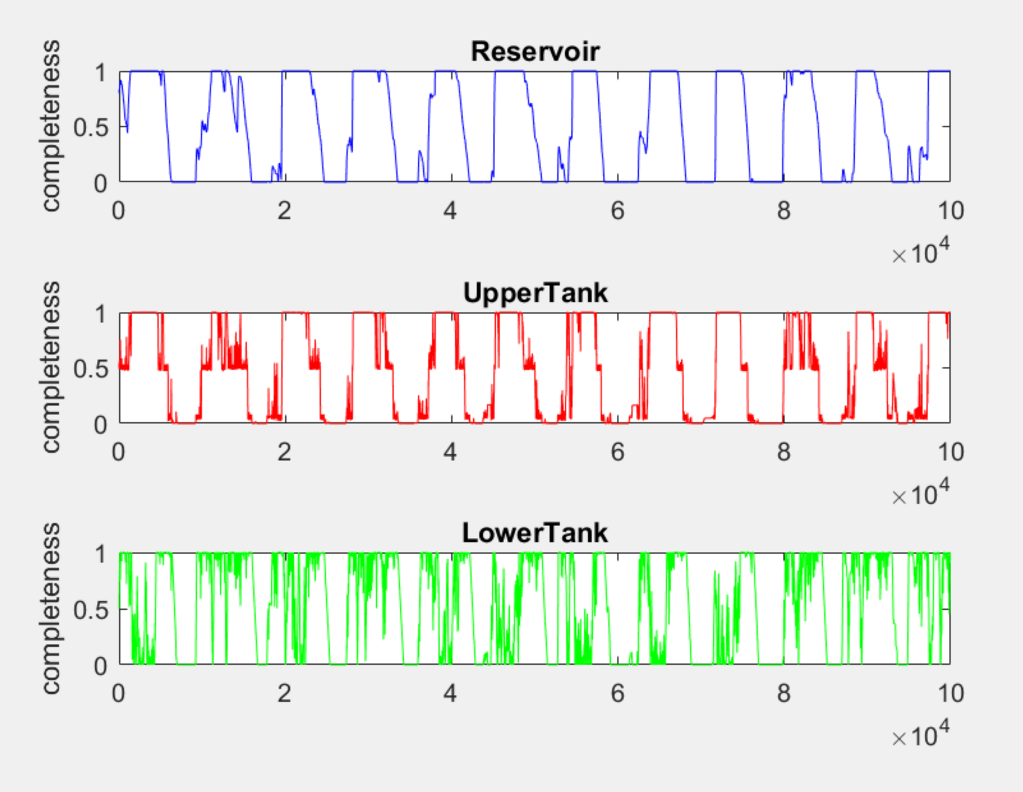
Regarding energy storage, given that water cannot be pumped to the reservoir, the only way to store energy surpluses is the lower tank-upper tank route. Given the small capacity of the two tanks, the energy storage of the system is quite low.

The final results of the simulation were:

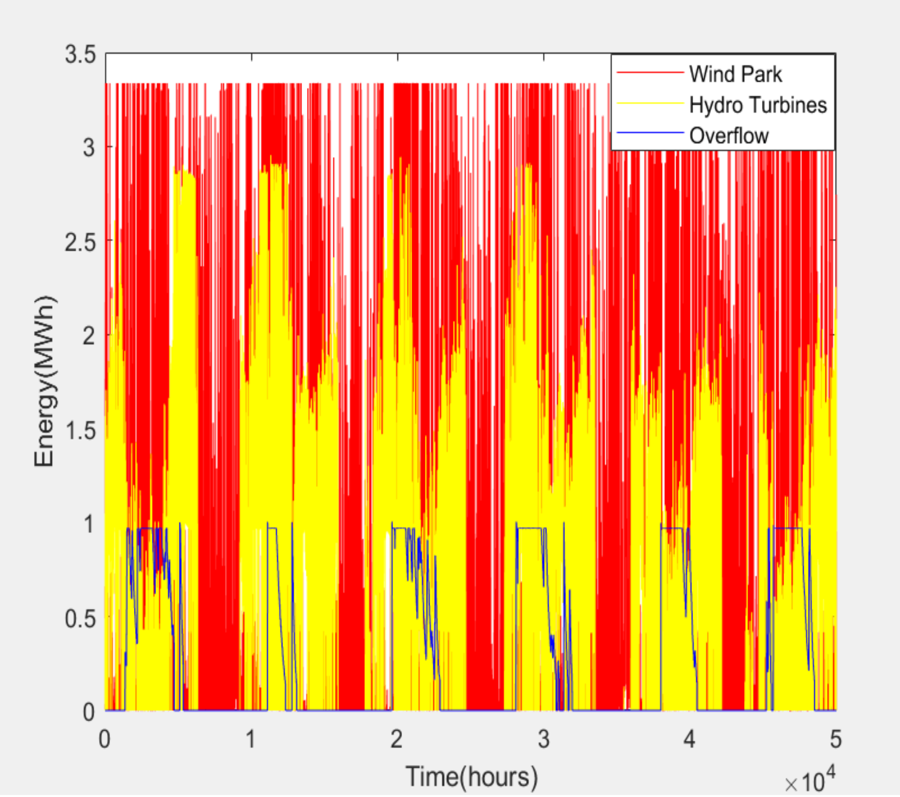
- Irrigation Reliability = 88,6%
- Irrigation Resilience = 0,003%
- Irrigation Vulnerability = 80,4 m^3
- Energy Generation Reliability = 58,4%
- Energy Generation Resilience = 0,001%
- Energy Generation Vulnerability = 1,15 MWh

In Graph 20, the time series of storage completeness of the reservoir, the upper tank and the lower tank are presented. The reservoir remains empty 27,5% of time, the upper tank 16,6% and the lower tank 24,0%.

The mean wind energy generation is 0,72 MWh, with standard deviation 1,1 MWh, while in 26,1% of the time steps energy was generated due to spill of the reservoir with mean value of 0,76 MWh per operating time step. Almost 47,7% of the hours of the simulation deficits should be encountered through the operation of the turbines. The mean value of their energy generation was 1,04 MWh per operating hour.



GRAPH 20: COURSE OF STORAGE COMPLETENESS FOR SIMULATION NO.3



GRAPH 21: ENERGY GENERATION MIXTURE FOR SIMULATION NO.3

Graph 21 presents the distribution of simulated energy by different sources. In particular, 50,7% of annual energy is generated from the wind park (6,23 GWh) and the rest from the hydroelectric stations, where 28,6% is produced due to reservoir spill (1,74 GWh) and 4,35 GWh are generated by the hydroelectric power plants.

Using the “guaranteed price” model for wind energy pricing which features no penalty, the wind park operator earns 527.000 €/year, while the annual earnings of the hydroelectric power plant operator are €1.283.250 (by setting the price of 295 €/MWh). Finally, the economic losses due to irrigation deficits are 1.612 €/year.

SIMULATION NO.4

Simulation No.4 is the most realistic, since it accounts for the seasonal restrictions set by PPC SA, but not the ability for pumping water to the reservoir.

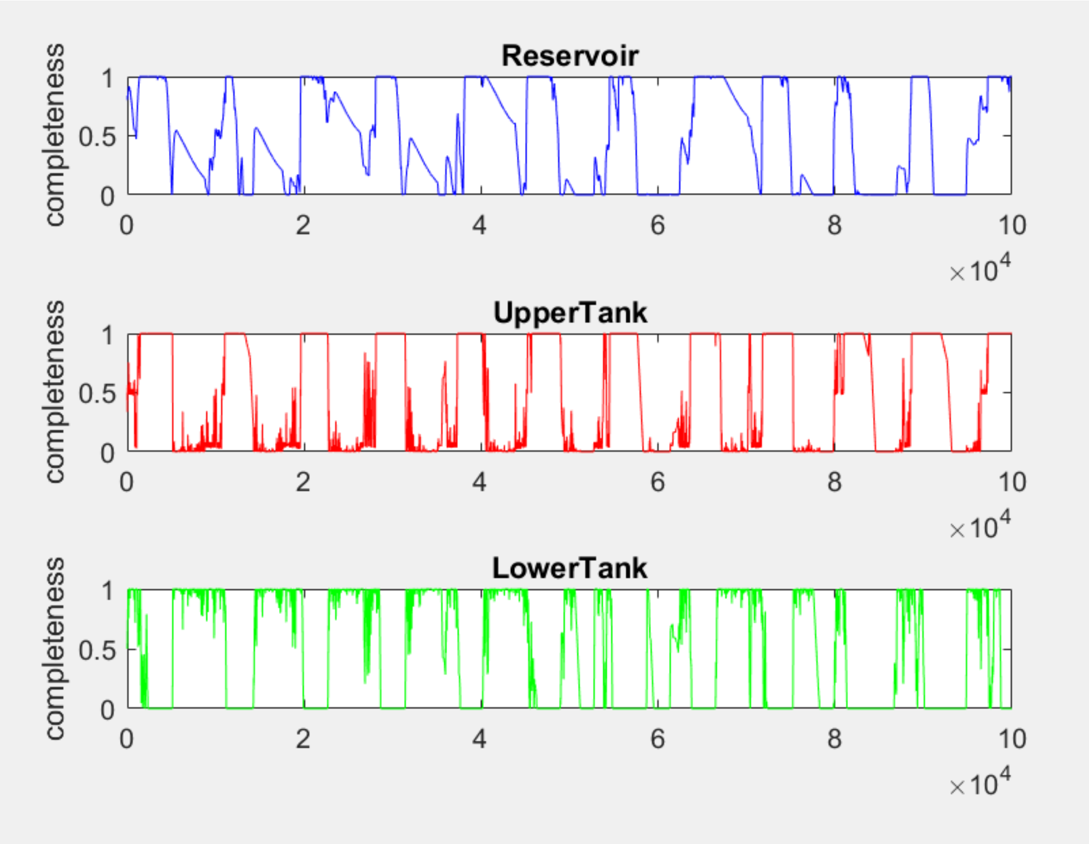
The criteria for deciding the proper route for energy generation are the following: between October and April, if the completeness of the reservoir is higher than the limit set by the seasonal restrictions, while the storage of the upper tank is lower than the one of the lower tank, or the completeness of the upper tank is below 5%, then the reservoir-upper tank route is selected for energy generation; otherwise the upper tank-lower tank one is used. As a result, the reservoir-upper tank route is chosen about 33% of time in which deficits occurred, while 67% of time energy is generated by releasing water from the upper tank.

Regarding energy storage, given that water cannot be pumped into the reservoir, the only way to store energy surpluses is the lower tank-upper tank route.

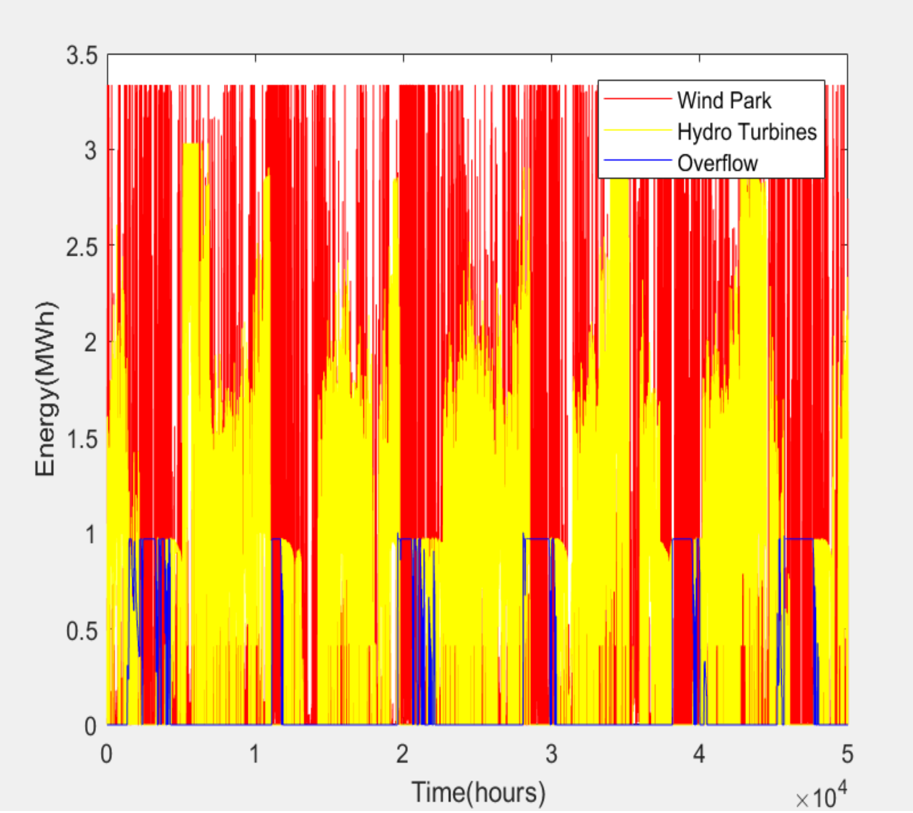
The final results of the simulation were:

- Irrigation Reliability = 92,9%
- Irrigation Resilience = 0,005%
- Irrigation Vulnerability = 112,6 m^3
- Energy Generation Reliability = 57,7%
- Energy Generation Resilience = 0,001%
- Energy Generation Vulnerability = 0,98 MWh

In Graph 22 the time series of the storage completeness of the reservoir, the upper tank and the lower tank for 100.000 hours are presented. The reservoir has no storage 24,4% of time, the upper tank 26,6% and the lower tank 41,3%.



GRAPH 22: COURSE OF STORAGE COMPLETENESS FOR SIMULATION NO.4



GRAPH 23: ENERGY GENERATION MIXTURE FOR SIMULATION NO.4

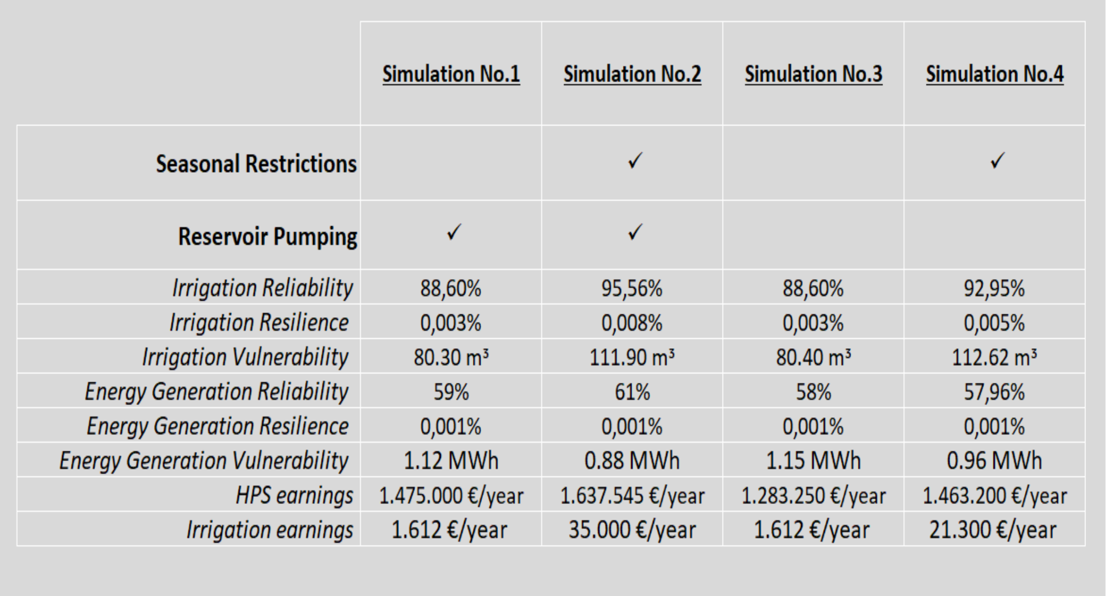
The mean hourly wind energy generation is 0,72 MWh, with standard deviation 1.1 MWh. In almost 21,6% of time, energy is generated due to spill of the reservoir, with mean hourly value of 0,81 MWh. Approximately 51% of time the turbines have deficits to encounter. Their mean hourly energy generation is 1,13 MWh.

Graph 23 presents the distribution of energy generation by different sources. In particular, 46,8% of the total annual energy arrives from wind turbines (6,23 GWh), 38,83% is produced directly from the hydroelectric stations (4,96 GWh) and the rest (1,53 GWh) is produced from reservoir spill. In this respect, the wind park operator earns 527.000 €/year and the operator of hydroelectric plants earns 1.463.200 €/year. Setting the irrigation pricing at 0,13 €/m^3 and its penalty at 1,04 €/m^3, the earnings during the simulation are 21.300 €/year.

COMPARISON AND CONCLUSIONS

Table 4 summarizes the key outcomes of the four simulations, investigating the impacts of seasonal restrictions and the ability of pumping water to the reservoir. As shown, enabling both options undoubtedly improves the system performance.

First, the operation of the hybrid system by applying the seasonal restrictions set by PPC SA not only increases the reliability of irrigation (as expected), but also improves the coverage of energy needs of the island. That is to say, the restrictions regarding the desirable reservoir level are used not only for setting irrigation as a priority of the system, but also ensure the rational operation of the hybrid system in total.



	Simulation No.1	Simulation No.2	Simulation No.3	Simulation No.4
Seasonal Restrictions		✓		✓
Reservoir Pumping	✓	✓		
Irrigation Reliability	88,60%	95,56%	88,60%	92,95%
Irrigation Resilience	0,003%	0,008%	0,003%	0,005%
Irrigation Vulnerability	80.30 m^3	111.90 m^3	80.40 m^3	112.62 m^3
Energy Generation Reliability	59%	61%	58%	57,96%
Energy Generation Resilience	0,001%	0,001%	0,001%	0,001%
Energy Generation Vulnerability	1.12 MWh	0.88 MWh	1.15 MWh	0.96 MWh
HPS earnings	1.475.000 €/year	1.637.545 €/year	1.283.250 €/year	1.463.200 €/year
Irrigation earnings	1.612 €/year	35.000 €/year	1.612 €/year	21.300 €/year

TABLE 4: AGGREGATED RESULTS OF DIFFERENT SIMULATIONS

Specifically, the difference between the first and the second simulation is about 7% in terms of irrigation reliability and 2% in terms of energy generation reliability, while the average energy deficit drops from 1,12 to 0,88 MWh. The wind park operator still earns the same amount of money due to the “guaranteed price” policy, while the hydroelectric power station operator earns 11% more money per year in simulation No.2. Concurrently, due to the high price of the irrigation penalty, the earnings from irrigation skyrocket from 1.612 €/year to 35.000 €/year. Moreover, the energy generation due to spill of the reservoir rose from 14% of the total energy generation in simulation No.1 to 22% in simulation No. 2.

Similarly, simulation No.3 differs from No.4 in terms of irrigation reliability. In detail, there is a small increase of about 3,6% from the third to the fourth simulation, while the reliability of energy generation remains practically constant. Simultaneously, the average energy deficit drops from 1,15 to 0,96 MWh. The wind park operator earns the same amount of money due to the “guaranteed price” model. The hydroelectric power station operator increases his earnings about 14% in simulation No.4. Concurrently, due to the high price of the irrigation penalty, the earnings from irrigation also show a rapid increase from 1.612 to 21.300 €/year. In both simulations, the energy generation due to spill of the reservoir is about 14% of the total energy generation, while the annual energy generation of the hydro turbines rose from 4,35 to 4,96 GWh/year.

By enabling water pumping into the reservoir, the improvement of the hybrid system’s outcomes is noticeable, but not as drastic as the previous factor. Specifically, the difference of the first and the third simulation are negligible and will not be examined. However, the differences between the simulations which use the seasonal restrictions are conspicuous, as the irrigation reliability of the system increases about 2,6% and the one of energy generation 3% from simulation No.4 to simulation No.2. At the same time, the average energy deficit drops from 0,96 to 0,88 MWh per failure, while the deficit of irrigation decreases about 0,70 m^3. The wind park operator’s earnings are the same and the ones of the hydroelectric power station operator rise approximately 12%. Regarding irrigation, its benefits are slightly increased from 21.300 to 35.000 €/year. In addition, the energy due to reservoir spill rose from 14% of total energy generation in simulation No.4 to 22% in the second simulation, while the annual energy generation by the turbines is increased by 12%.

Conclusively, both factors defining the alternative management models of the system influence remarkably the outcomes of the hybrid system and, most of all, its reliability. The simulation No. 2 which features the seasonal restrictions and the water pumping into the reservoir has, undoubtedly, the best results of all. Despite this fact, simulation No.4 approaches reality more than any other scenario, as it resembles the operation policy set by PPC SA.

CHAPTER 6: OPTIMIZATION

The results of the hybrid energy system's operation were presented in the previous chapter. In this chapter, the possibility of optimizing the system components and their effect on the reliability are examined. Furthermore, conclusions are drawn regarding the possibility of improving the operation of the system, by means of economic criteria.

The purpose of optimization is to achieve the most suitable design under a set of prioritized criteria and constraints, including maximization of reliability for irrigation and energy uses. Key components of the problem are the objective function, expressing the main aim of the model, which is either to be minimized or maximized, and a set of unknowns or variables which control the value of the objective function. The coefficients of the objective function indicate the contribution to the value of the objective function of one unit of the corresponding variable.

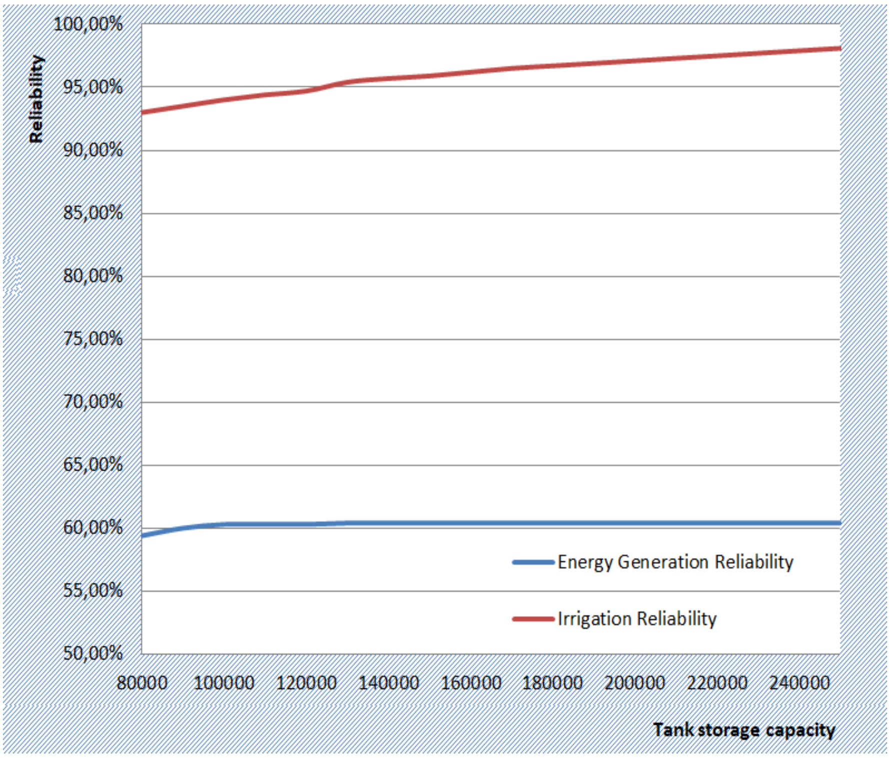
In our case, the operation of the hybrid energy system determines the objective function of the optimization procedure. The results of the objective function are going to be examined through single-variable optimization using the storage capacity of the tanks, the pump station's nominal power and the energy generation decision criteria of the reservoir and the upper tank. In addition to this, a genetic algorithm is going to provide results regarding the multicriteria optimization of the hybrid energy system, in an attempt to define the most effective operation of the system.

SINGLE-VARIABLE OPTIMIZATION

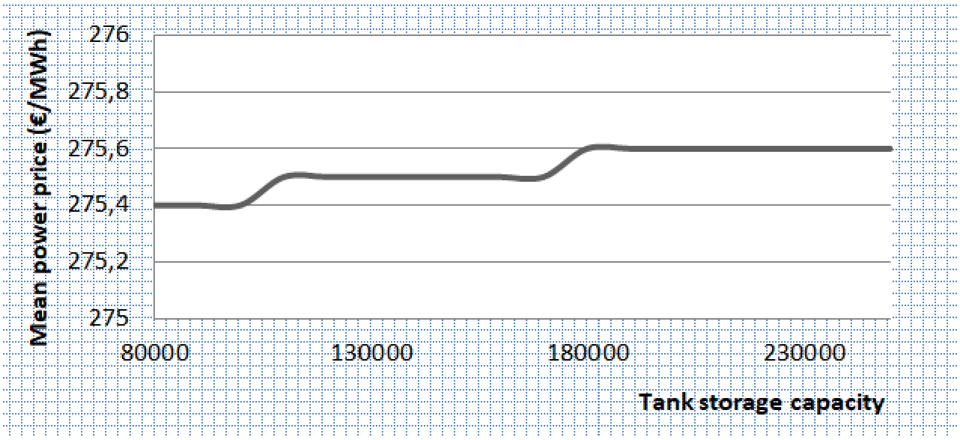
TANK STORAGE CAPACITY

The storage capacity of the upper and the lower tank is 80.000 m³. Increasing this size would result to larger potential of energy storage, leading to higher exploitation of wind energy. Moreover, the reservoir-upper tank route is going to be chosen less times if the completeness of the upper tank is higher, leading to larger amounts of water covering the irrigation needs of the island.

Graph 24 presents the irrigation and energy generation reliability for tank storage capacities from 80.000 m³ to 250.000 m³.



GRAPH 24: IRRIGATION AND ENERGY GENERATION RELIABILITY VS. TANK STORAGE CAPACITY



GRAPH 25: MEAN POWER PRICE PER MWH FOR DIFFERENT TANK STORAGE CAPACITIES

As shown, the effect of the storage capacity to the energy generation reliability is insignificant. On the contrary, a configuration of tank storage capacity to 250.000 m³ would increase the irrigation reliability of the system by 5,4%. This means that the earnings due to irrigation would increase about 130%, up to 48.281 €/year.

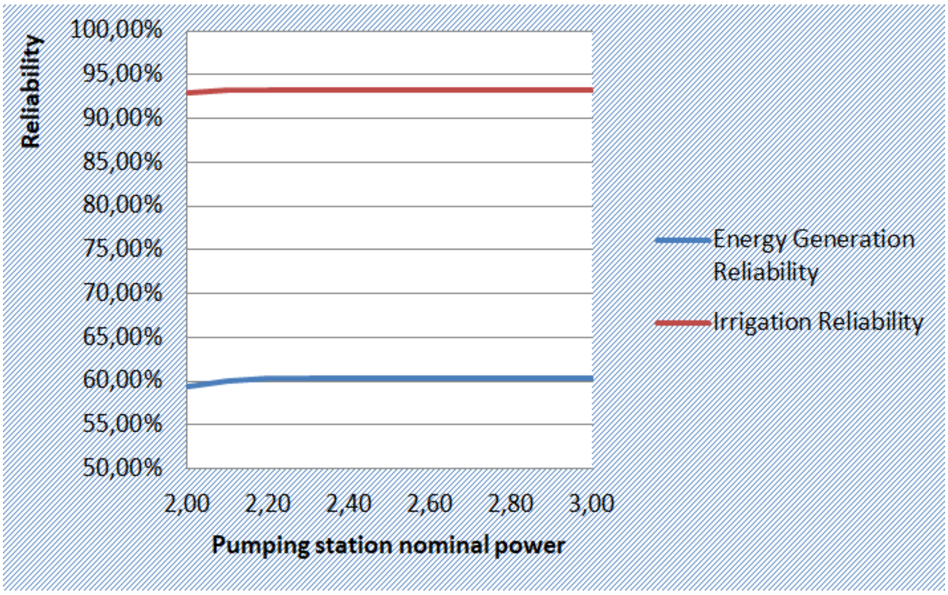
The power price does not have significant differentiations when alternating the tank storage capacity. When the storage is 80.000 m³, the mean power price is about 275,4 €/MWh and with the storage being 250.000 m³, this is about 275,6 €/MWh.

Graph 25 presents the mean power price per MWh, provided from the “guaranteed price” model, for tank storage capacities from 80.000 m³ to 250.000 m³.

PUMP STATION NOMINAL POWER

The maximum energy surplus that the can be pumped to higher water levels is 2 MWh per simulation hour. By increasing the nominal power of the pump station it is possible to exploit larger energy surpluses and encounter more effectively the stochasticity of wind energy generation.

In Graph 26 the irrigation and energy generation reliability for pumping station installed power from 2 MW to 3 MW are presented.



GRAPH 26: IRRIGATION AND ENERGY GENERATION RELIABILITY VS. PUMPING STATION POWER

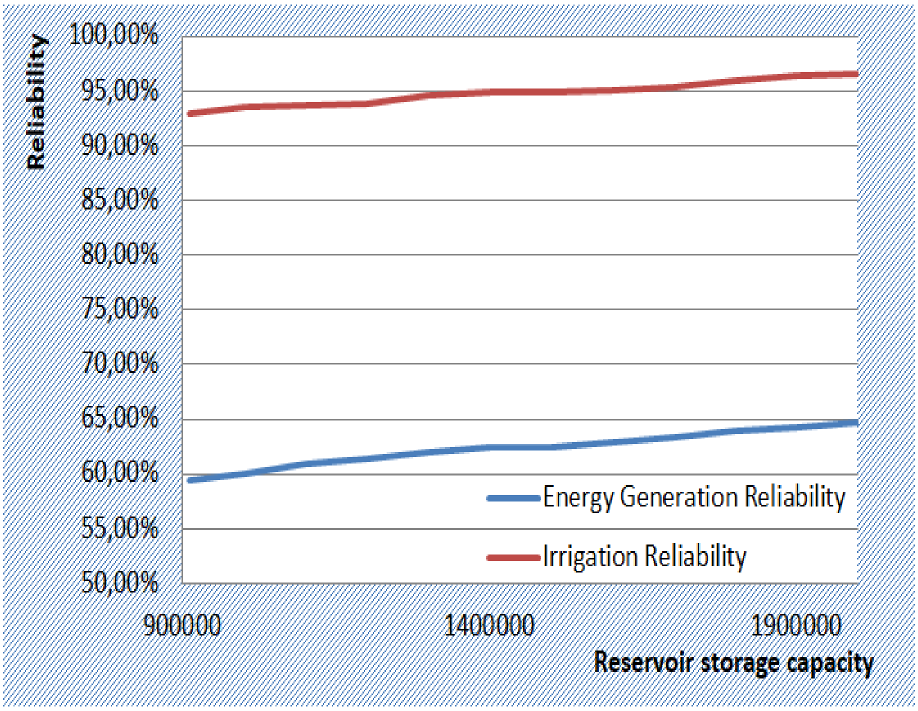
As shown above, the effect of the pumping station power to the irrigation reliability and the energy generation reliability is insignificant.

Moreover, the power price does not have significant differentiations when changing the pumping station power. Specifically, for any value between 2 MW and 3 MW power the mean power price is about 275,4 €/MWh.

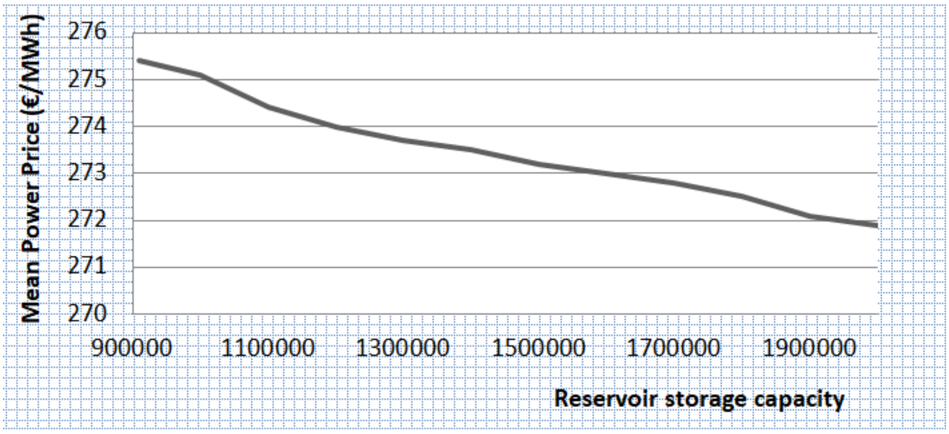
RESERVOIR STORAGE CAPACITY

The storage capacity of the reservoir is 910.000 m^3. Increasing this size would lead to larger potential of energy storage and larger amounts of water able to cover the irrigation demand of the island.

Graph 27 presents the irrigation and energy generation reliability for reservoir storage capacities from 910.000 m^3 to 2.000.000 m^3.



GRAPH 27: IRRIGATION AND ENERGY GENERATION RELIABILITY VS. RESERVOIR CAPACITY



GRAPH 28: MEAN POWER PRICE VS. RESERVOIR CAPACITY

The effect of the reservoir storage capacity to the energy generation reliability and the irrigation reliability is notable. In particular, doubling the capacity of the reservoir leads to a 5% increase of the energy generation reliability and a 3,5% increase of the irrigation reliability. Hence, the earnings due to irrigation would be about 39.900 €/year.

The power price drops remarkably when alternating the reservoir storage capacity. When the storage is 910.000 m³, the mean power price is about 275,4 €/MWh and with the storage being 2.000.000 m³, the mean power price decrease about 1,3% to 271,9 €/MWh.

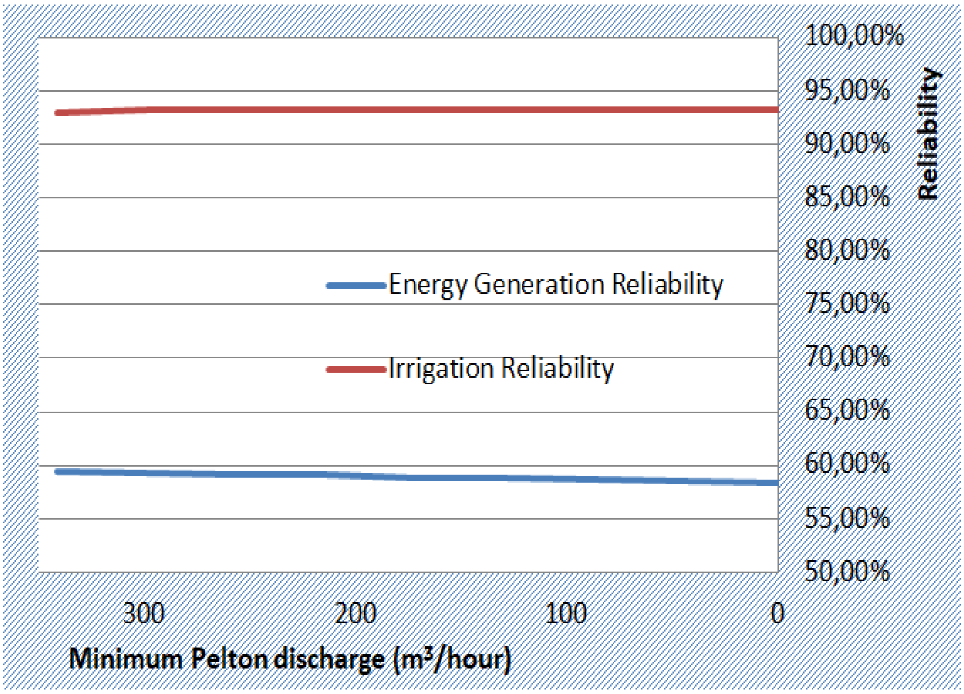
Graph 28 presents the mean power price per MWh, as calculated from the “guaranteed price” model, for reservoir capacities from 910.000 m³ to 2.000.000 m³.

MINIMUM PELTON DISCHARGE

The minimum operational discharge of the Pelton turbine is equal to 0,13 Q_D = 340 m^3/h. In about 7-10% of time, the reservoir or the upper tank are forced to release this amount of water in order to generate energy for insignificant deficits. As a result, more water is placed in lower levels and is not exploitable for energy generation and coverage of irrigation needs.

Graph 29 presents the irrigation and energy generation reliability against minimum Pelton discharge, ranging from 340 m^3/h down to zero.

As shown, the effect of the minimum Pelton discharge to the irrigation reliability and the energy generation reliability is not notable.



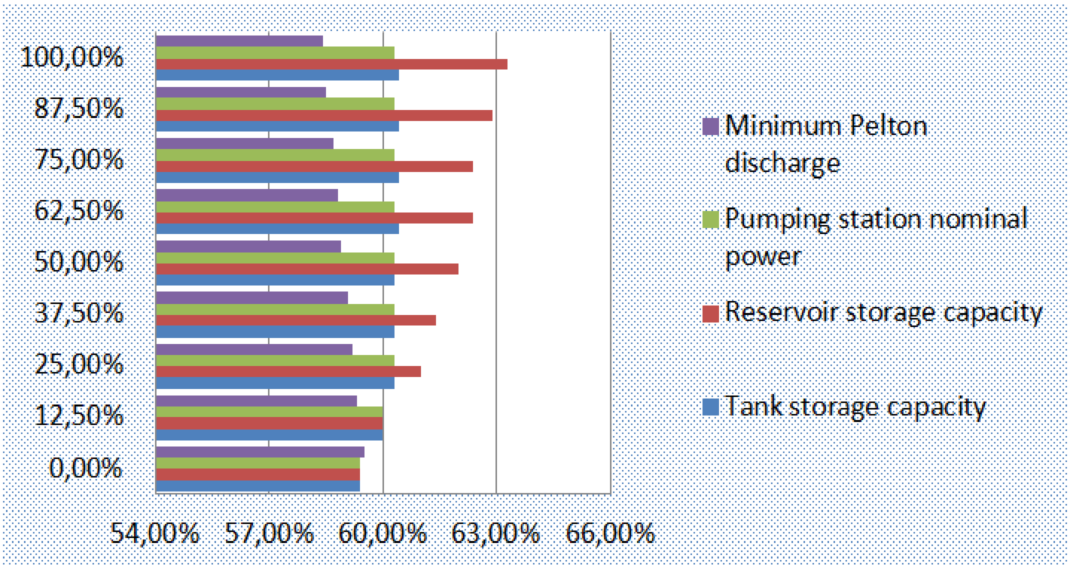
GRAPH 29: IRRIGATION AND ENERGY GENERATION RELIABILITY VS. MINIMUM TURBINE FLOW

In addition, the power price does not have significant differentiations for different minimum discharge values. In particular, for any value between 340 m^3/h and 0 m^3/h the mean power price is about 275,40 €/MWh.

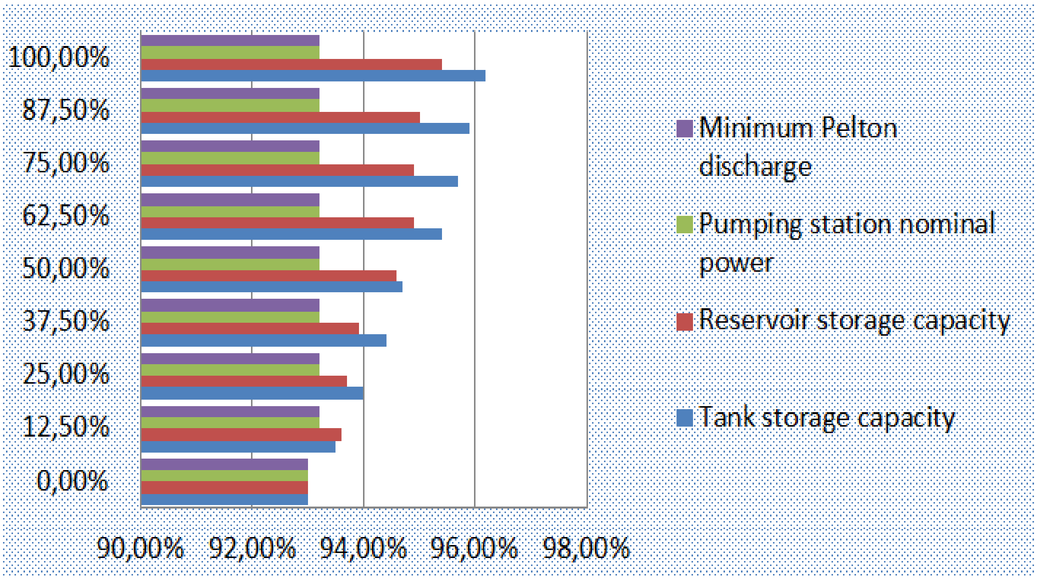
AGGREGATED RESULTS

The effects that the different variables have to the outcomes of the hybrid energy system are dissimilar. In order to process a multifactorial optimization it is needed to know the sensitivity of the system results to all the variables. Graph 30 presents the sensitivity of the energy generation reliability to the reservoir and tank storage capacity and the pumping station power.

Undoubtedly, the reservoir storage capacity is the variable affecting the energy generation reliability the most. Furthermore, increasing the tank storage capacity is slightly more important in terms of energy reliability than improving the pumping station's nominal power.



GRAPH 30: SENSITIVITY OF ENERGY GENERATION RELIABILITY



GRAPH 31: SENSITIVITY OF IRRIGATION RELIABILITY

In Graph 31 the sensitivity of the irrigation reliability to the reservoir and tank storage capacity, the pumping station power and the minimum discharge is shown.

The tank storage capacity is the variable affecting the irrigation reliability the most, while the reservoir storage capacity is also of high importance. The pumping station's nominal power and the minimum discharge with which the Pelton hydro turbine can produce hydro power influence slightly the outcome of the hybrid energy system regarding irrigation.

MULTICRITERIA OPTIMIZATION

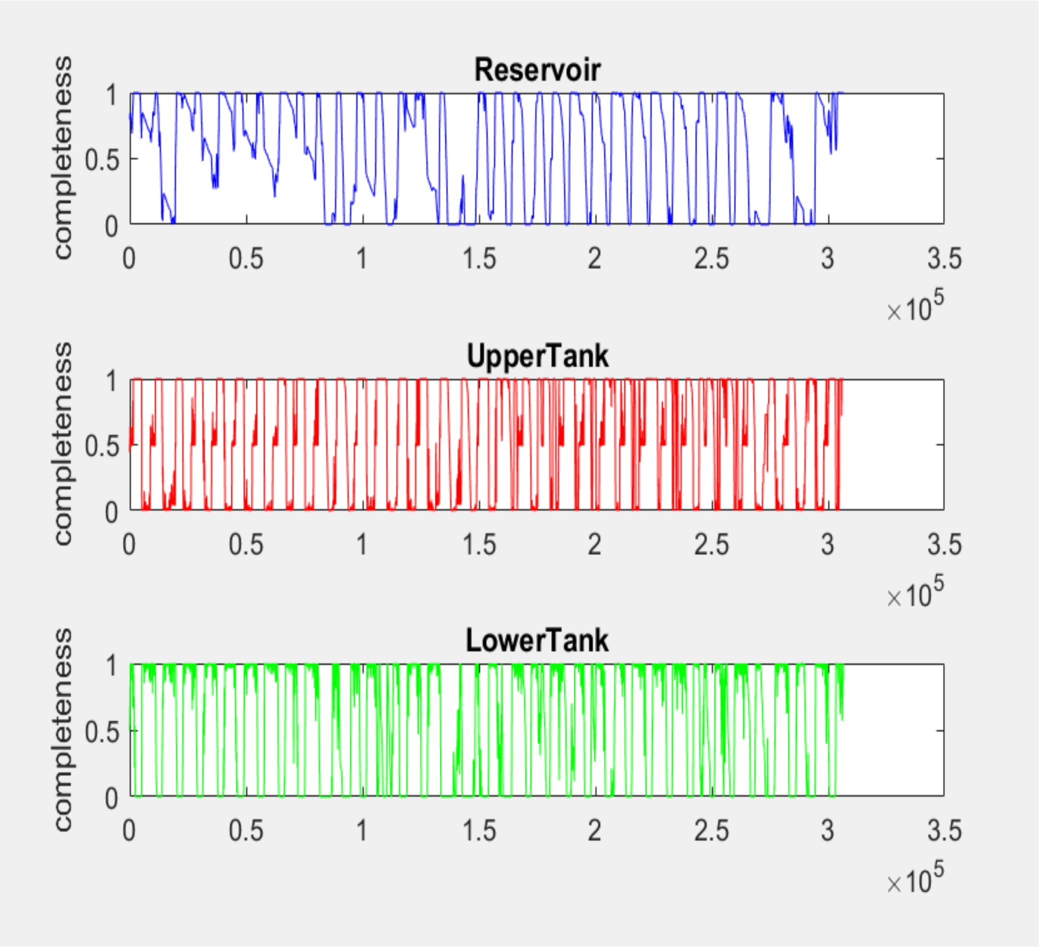
The performance of the hybrid energy system is affected by several factors. The most important is the capacity of the reservoir and the tanks, as they determine the potential water storage of the system. The power of the pumping station and the minimum discharge of the hydro-turbine also influence the outcomes. Hence, the optimization of the hybrid energy system has to be one of all the variables simultaneously. For this purpose, a genetic algorithm was developed in an attempt to define the optimal system operation, in which irrigation reliability reaches 98,5%.

The genetic algorithm is a method for solving both constrained and unconstrained, optimization problems, based on natural selection, i.e. the process that drives biological evolution. The algorithm repeatedly modifies a population of individual solutions. It begins by creating a random initial population, and then creates a sequence of new populations, by using s parents the individuals in the current generation, relying on bio-inspired operators (mutation, crossover and selection).

The results show that in order to achieve irrigation reliability equal to 98,52%, featuring an average failure of about 120,8 m^3, the storage capacity of the reservoir has to be at least 2.680.000 m^3, the one of the tanks 197.000 m^3, the nominal power of the pumping station at 2.200 kW, and the minimum discharge with which the Pelton hydro turbine can produce hydro power below 286 m^3/h. Concurrently, for these values of the variables the energy generation reliability is equal to 65,81% and its vulnerability circa 0,77 MWh. The reservoir has no storage 12,4% of time, the upper tank 22,5% and the lower tank 31,7%.

Using the "guaranteed price" pricing model, it is estimated that the wind park operator earns 527.000 €/year and the operator of hydroelectric plants earns 1.741.200 €/year. Setting the irrigation pricing at 0,13 €/m^3 and its penalty at 1,04 €/m^3, the earnings during the simulation are 50.430 €/year. If the autonomous power station covered all the deficits for a price of 350 €/MWh, its earnings would be approximately 811.200 €/year. As a result, the average power price of the island Ikaria would be about 251 €/MWh.

Graph 32 presents the time series of storage completeness of the reservoir, the upper tank and the lower tank for the simulation of the hybrid energy system with the aforementioned optimal values.



GRAPH 32: TIME SERIES OF COMPLETENESS OF THE RESERVOIR AND THE TANKS FOR THE OPTIMAL HES SIMULATION

CHAPTER 7: ENERGY MARKET

ABOUT THE OPERATION OF THE ENERGY MARKET

To achieve 100% reliability on the fulfilling of energy demand across the island it is necessary to use the power station of Agios Kirikos. In general, the operating costs of conventional production units in the remote islands are high due to rising transport costs and environmental taxes. Specifically, in Ikaria the pricing for the energy generated from the autonomous power station of Agios Kirikos is set at 350 €/MWh. Therefore, in this chapter it will be examined whether the "guaranteed price" pricing model for the three energy producers of the island or a more "liberal" energy market between those three energy players will improve the operation of the system. Moreover, we will examine which of the two suggested management models will offer the lower power price to the public and which one will achieve maximization of the power players' earnings. In order to employ such complex simulations, an extended code on Matlab® was developed featuring the operation of the hybrid energy system and an energy market. Apart from comparing the different management models of the energy generation profile of Ikaria, this simulation aims at encountering the problematic of setting an energy market on a non-interconnected island and optimizing its parameters.

There are two major arguments opposing the operation of an energy market in a non-interconnected island:

- Firstly, the stochastic nature of the power produced by RES units and their limited ability to control their power will make it doubtful that the operation and performance of such facilities in remote areas is profitable. Thus, it is argued that only by securing a "guaranteed price" for every proportion of energy generated by RES installations, even if it is not being exploited by the energy grid, investors will have motivations to invest in RES units in remote islands, leading to higher exploitation of their wind potential and contribution to the attainment of the 20-20-20 targets set by EU. Nevertheless, in Ikaria the aforementioned arguments are encountered by the characteristics of the island's hybrid energy system. On the one hand, the significant wind potential of the island leads to higher proportions of energy production and, consequently, the chance of making more antagonistic offers during the energy auction. In addition to this, the ability of the system to store energy surpluses, which account for circa 38% of the wind energy generation, makes the investment even more profitable.
- Secondly, the possibility of the three energy players forming a cartel, taking advantage of to their minor number. This is encountered by considering a hypothetical operator of the hybrid energy system who sets maximum values

on bidding. Moreover, the adaption of a pricing model based on discrimination of the prices will be examined instead of the existing Limit Price System, which undoubtedly favors the collusion of the energy players in order to maximize their profits.

The main goals of the operation of the energy market are the minimization of the power price, its comparison with the fixed value of 295 €/MWh set by PPC, and the energy price in case that the autonomous power station was the only source of energy and securing earnings for the energy players that allow the depreciation of their investments and offer incentives for sufficient profits.

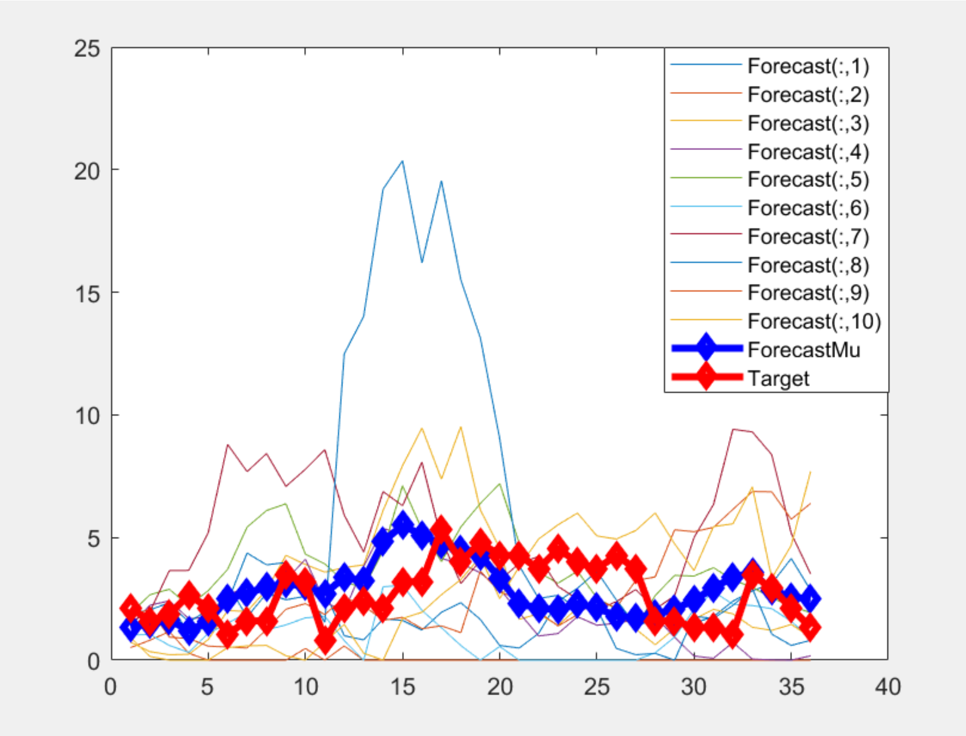
Setting up the energy market needed the confrontation of major impediments and the development of empirical procedures that reflect the real-time operation of the system, which will be presented next.

WIND SPEED FORECASTING

As mentioned above, the energy auction takes place daily at t_0 =12:00 am and defines the energy generation mixture of the day ahead. Hence, the forecasting of the hourly wind speed leading to the energy generation is necessary.

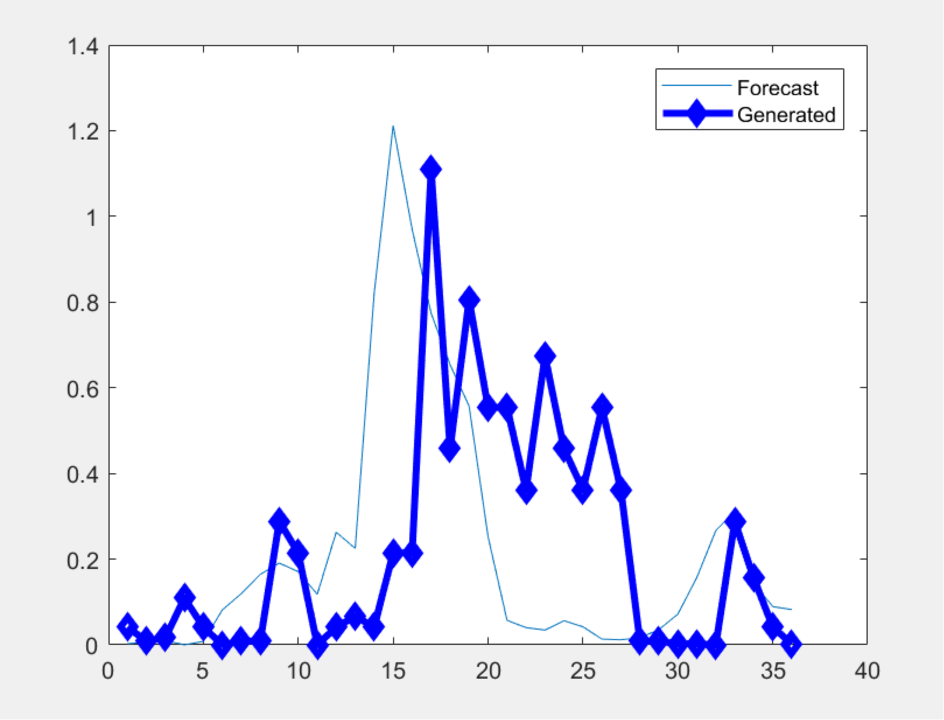
For real-time energy market simulations, we developed an innovative forecasting procedure, to provide stochastic projections of the upcoming wind speeds up to 36 hours lead time, by running each day at 12:00 am (t_0) and estimating the upcoming wind speed from time step t_0 + 12 up to t_0 + 36 (hours). Initially, we employed SPARTA for generating 1.000 years of synthetic hourly wind speed data, which were next used as income for a K-Nearest Neighbors Algorithm (KNN). The latter simply stores a collection of examples. Each example consists of a vector of features (describing the example) and its associated class (for classification) or numeric value (for prediction). Given a new example, KNN finds its *k* most similar examples (called nearest neighbors), according to a distance metric, and predicts its class as the majority class of its nearest neighbors or, in the case of regression, as an aggregation of the target values associated with its nearest neighbors.

In general, ten realizations of hourly wind speed for the entire simulation horizon were provided. An example for 36 hours lead time, by combining SPARTA with KNN, and their mean value are presented in Graph 33,



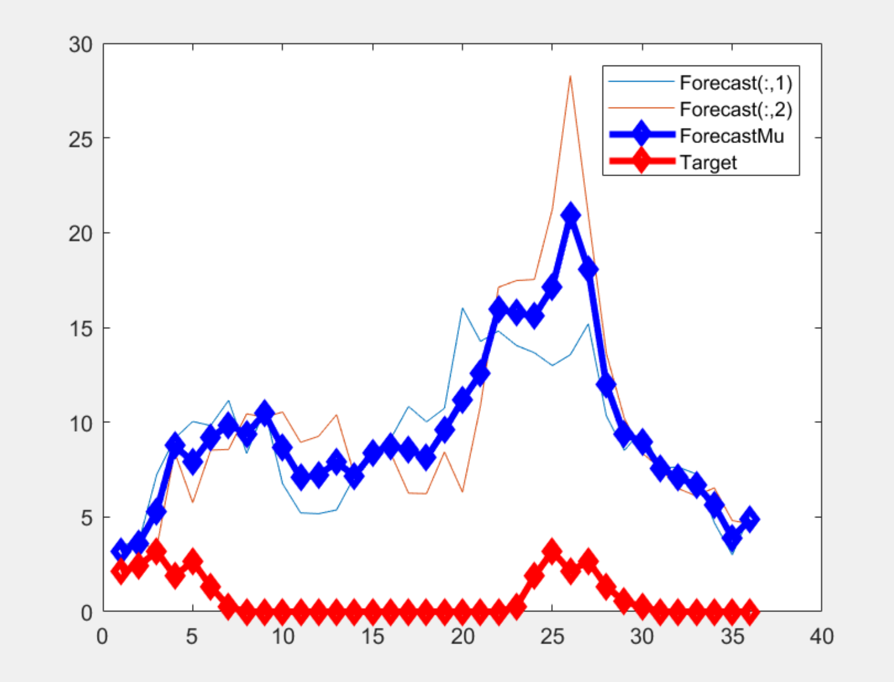
GRAPH 33: TEN FORECAST SETS OF WIND SPEED FOR 36 HOURS LEAD TIME

Due to the upper and lower bound of the wind turbines' power curve, converting the forecasted and observed wind speed to forecasted and observed energy generation results to smoother deviations. For example, Graph 34 shows the forecasted and observed energy generation of the simulation previously presented in Graph 33:



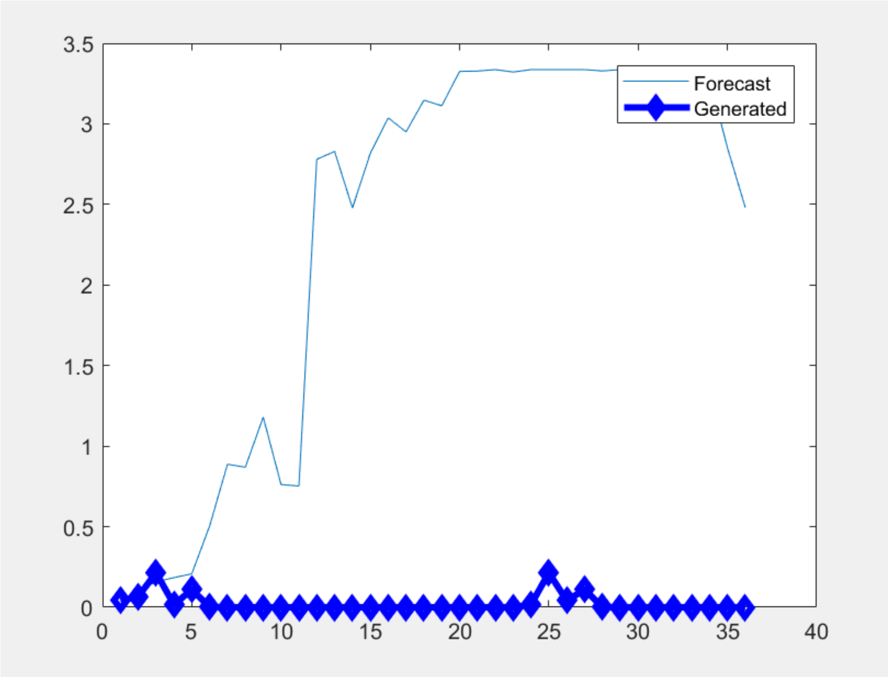
GRAPH 34: AVERAGE FORECAST AND OBSERVED ENERGY GENERATION REFERING TO GRAPH 24

Undoubtedly, by reducing the number of realizations of the wind forecasting model, larger deviations appear between the observed and forecasted wind speed (Graph 35).



GRAPH 35: TWO FORECAST SETS OF WIND SPEED FOR 36 HOURS LEAD TIME

Consequently, the energy generation forecast under a minor number of realizations differs notably from the actual energy generation (Graph 36).



GRAPH 36: FORECASTED AND OBSERVED ENERGY GENERATION REFERING TO GRAPH 26

Hence, the aforementioned forecasting procedure can predict satisfactorily the wind speed at a lead time of three or four hours, but the lead time of 36 hours presents remarkable differentiations of the observed and forecasted wind speeds. Hence, the operation of the energy market simulation cannot be evaluated when using predictions so different from the actual values. Therefore, the results of the energy market simulation will be tested with the hypothesis of enabling a meteorological forecasting procedure, whose accuracy (in terms of wind power production) is empirically estimated at about 90-95%.

PRICING MODEL

The existing legislation in Greece imposes the implementation of a “guaranteed price” model for RES. According to PPC SA, the fixed value set for the hybrid energy generated from Ikaria’s hybrid energy system is 295 €/MWh. In addition to this, the operation costs of the autonomous power station in Agios Kirikos are about 350 €/MWh, while as shown in Table 1, the “guaranteed price” for the wind parks in the non-interconnected network is 84,60 €/MWh, regardless of whether the generated energy enters the grid or not. Although it is argued that by implementing a “guaranteed price” pricing model there will be incentives for higher RES penetration, especially in remote islands, this is expected to lead to notable expenses.

The existing pricing model for the operation of energy markets is the Limit Price System. This is defined as the price at which the electricity market is cleared and is the price received by all those who inject energy into the energy grid and are paid by all those who request energy from this. In particular, the Limit Price of the System is shaped by the combination of the price and quantity bids made each hour of the available power generation units and the hourly electricity that is demanded on an hourly basis by consumers.

A simple description of how the System's Limit Price is calculated mentions that the production units are ranked according to their bids in ascending order, starting from the lowest price offered for a certain amount of energy and ending at the highest bid. At the point where the energy offers reach the requested load, the Limit Price of the System is also determined. In essence, the System Limit Value coincides with the bid of the last unit to operate to meet demand. Figure 33 presents an example of the determination of the Limit Price of the System.

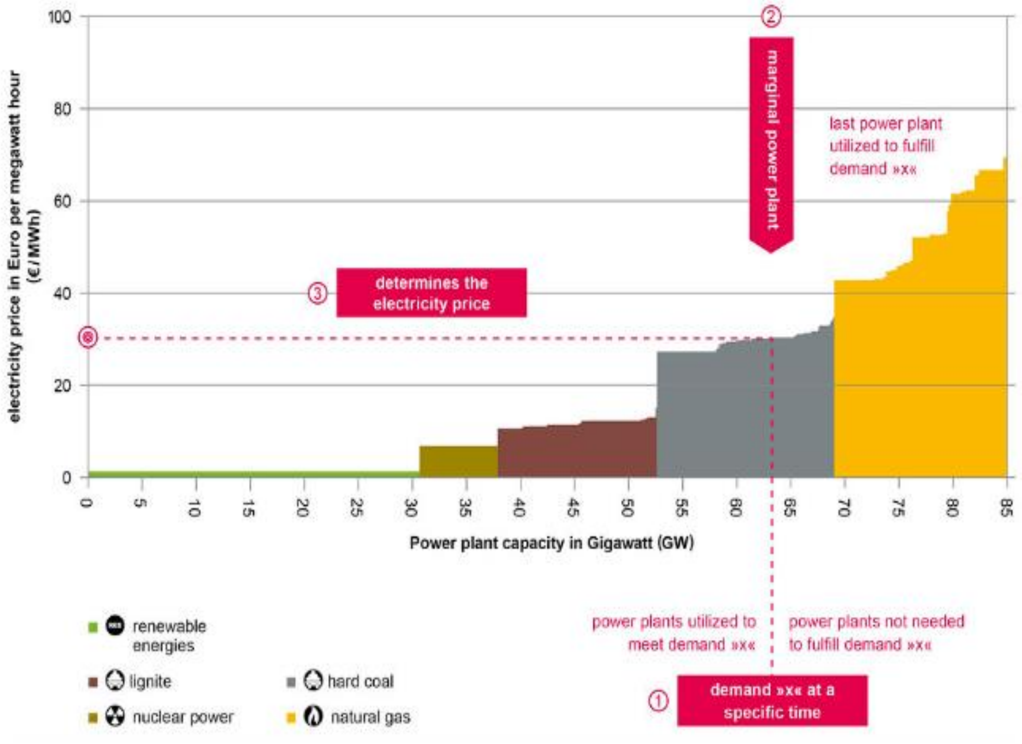


FIGURE 33: DETERMINATION OF LIMIT PRICE (SOURCE: OEKO INSTITUTE)

In order to protect consumers and create conditions of healthy competition, an upper limit on the price offered in the interconnected grid is set at 150 €/MWh, and a lower bidding level, which is the variable cost of the unit, is put in place, so that in most cases producers will have to pay their fuel costs. Nevertheless, due to the special conditions met in the non-interconnected grid, the upper limit for the purpose of simulating the energy market of Ikaria is set at 350 €/MWh, equal to the cost of the autonomous power station.

Despite the operation of the Limit Price System in the interconnected grid, it is argued that its implementation in remote islands will lead to higher chances of the energy players forming a cartel and purposely letting the autonomous power station enter the market so that the Limit Price reaches its upper bound. In this case, the earnings of all the energy players will be maximized without even providing all the energy they could generate.

Ikaria's energy market will also be simulated with the use of a pricing model based on discrimination of the prices instead of the existing Limit Price System. According to this model, the cumulative price of the generated power in each time step will come from the weighted value of energy production. By the term weighted, it is meant that the price of energy will be a sum of the proportion of energy each producer generated multiplied by the price each proportion was agreed to be sold during the energy auction. As a result, the profit of each player will be restricted only to the offer made during the energy auction and the competition among them will be embraced.

Moreover, it is necessary to impose penalties to the energy players in case that they do not achieve to provide the energy they agreed to during the auction. This measure will force them making far more realistic offers, based on their energy generation capacity at the certain moment and, consequently, conditions of healthy competition will be created. Otherwise, the energy players will have the incentive to agree on providing unrealistic energy offers, regardless of their ability to produce such amounts.

To sum up, all of the proposed pricing models are going to be examined during the simulation of the hybrid energy system in an attempt to define the one that provides the lowest power price to the public and draw conclusions on the operation of the energy market.

SURPLUS MANAGEMENT

The surpluses of energy during the operation of the hybrid energy system are used to pump water into higher levels, in order to store it as hydrodynamic energy. Surpluses are mostly created due to the stochastic nature of the wind energy generation. In particular, the energy generated from the wind park in many cases exceeds the corresponding demand of the island and, as a result, the pumped storage system is activated to store the energy surplus. In addition to this, during the operation of the energy auction and due to the failure of the wind speed forecasting procedure, it is possible that larger proportions of energy than agreed are generated. As a result, the energy demand is covered by one of the other two energy players and the surplus of wind energy is stored.

Energy surpluses can also be created from the autonomous power station, which has response time of approximately 20-25 minutes. Therefore, it is taken into account that the autonomous power station can respond in any energy deficit in the hourly scale and secure the maximum energy generation reliability of the system. In order to do so, the power station has to be operating at least at 300 kW. Otherwise, its response time is increased to several hours, even a day. Hence, in cases that the demanded power from the autonomous power station is less than 300 kWh within an hour, energy surpluses are created and need to be stored.

During the real-time simulation of the energy market, two major issues govern the management of energy surpluses.

First, the hydroelectric power station operator has the chance to buy energy surpluses by the other two players, probably on a fixed price set before the start of the hybrid energy system's operation, and use it to pump its water on higher levels in order to increase its energy storage. In contrast, an alternative management model is that the wind park and autonomous power station operators use their energy surpluses in order to rent storage of the lower tank and pump it to the upper tank. As a result, the strategy of the wind park operator will change when bidding in the energy auction, as he may have enough energy storage to handle the stochastic nature of its energy generation, leading to making more antagonistic offers than its competitors. Therefore, the interest of the hydroelectric power station operator is prohibiting the wind park storing large amounts of energy.

Second, the determination of the part of the storage capacity that the hydroelectric power plant operator will provide to the other two players to store their energy surpluses. On the one hand, the operator has the incentive of gaining earnings. However, by letting them getting more amounts of stored water will lead to the wind park operator making more antagonistic offers in the future and, consequently, putting the hydroelectric power plant out of the market. Thus, it is decided that the maximum allowed storage to be offered to the wind park and the autonomous power stations operators will be defined according to the month of operation.

All aforementioned surplus management models will be examined in an attempt to draw conclusions on the operation of the energy market.

TURBULENT CHARACTER OF WIND ENERGY

Wind turbines generate electricity from turbulent wind. Large fluctuations, and, more importantly, frequent wind gusts cause a highly fluctuating electrical power feed into the grid. Such effects are the hallmark of high-frequency turbulence.

Modern design enables variable rotational speed in order to optimize aerodynamic performance and reduce mechanical loads. AC-DC-AC inverters must then be used between the generator and the grid to match the specified grid frequency, thus decoupling the rotating mechanical parts of wind turbines from the grid. In this decoupled configuration, the controller of the wind turbine commonly operates freely to maximize his output; i.e., to follow the wind power fluctuations mostly regardless of the grid load. Furthermore, the typical reaction time of wind turbines is in seconds, so that the grid dynamics in this time range become more complex.

More fundamentally, understanding and reliably predicting wind dynamics remains a central issue in wind forecasting. The widely used hypothesis of a spectral gap allows to conveniently separating the dynamics of microscale turbulence from mesoscale climatology. This hypothesis supports the historical use of ten minute-averaged data records that supposedly contain all mesoscale dynamics without high-frequency turbulence. While mesoscale predictions are a central focus of energy meteorology, high-frequency fluctuations are seldom addressed (Milan *et al.*, 2013).

ENERGY MARKET STRUCTURE

The energy auction regarding the next 24 hours takes place daily, at t_0 = 12:00 am. First, the hourly wind speed from time steps t_0 + 12 to t_0 + 36 is estimated by the aforementioned forecasting procedure and then the three players make their offers against the projected energy demand (24 hourly values).

The offer of the Wind Farm (WF) accounts for the forecasted energy and aims at least to the depreciation of the investment. When strong winds are expected, the WF is considered to be the most competitive player. The penalty that is imposed to the WF, if it does not generate the promised amount of energy, is relatively low, in order to favor renewable sources that are inherently highly uncertain.

The criteria of the configuration of the Hydroelectric Power Station (HPS) offer are the completeness of the reservoir and the upper tank and the seasonally-varying restrictions that are imposed due to irrigation demands. The offers of HPS are generally higher than the ones of WF. Under some premise, e.g., during the winter and under high water storage, HPS is allowed to offer lower prices than WF, in order to enter the market and gain from the surplus of energy provided the other two players, through pumped-storage. In general, the configuration of the HPS offer is remarkably difficult due to the plethora of factors concerning its availability, as well as the relatively high penalty that is imposed in case of deficits.

The offer of the Autonomous Power Station (APS) is significantly higher than the other ones, owning to the cost of the oil transport and environmental taxes. The energy demand is mostly fulfilled by the WF and HPS, thus leaving to the APS the role of covering the deficits, in order to maintain the reliability at 100%. Since for technical reasons the operation of APS cannot be terminated, energy surpluses are quite often and they are regulated by the pumped-storage system.

According to a predetermined procedure, the energy players make offers regarding ten different levels of demand. Since the required power of Ikaria does not exceed 3 MW at ~96% of time, it is chosen that in the simulation of the energy auction the nine first energy demand levels will refer to the first 3 MWh of each time step, while the last level will refer to the energy demand that exceeds 3 MW. Hence, each one of the nine first levels will be offers referring to one third of one MWh, cumulatively 3 MWh, and the last one to rest of energy demand above 3 MWh.

ENERGY MARKET'S OPERATION

The simulation of the operation of the hybrid energy system's energy market was developed in Matlab®. The code runs a simulation procedure of 35 years using an hourly time step. For the operation of the energy market, all possible scenarios that were mentioned in the previous chapter were examined. The simulation consists of many phases which resemble the different functions of the energy market.

First, at each time step the discharge capacity of each route is calculated on the basis of the nominal power of the two turbines, the distance between the reservoirs and the rate of turbine efficiency.

Then, the reservoir spill takes place. At each step the runoff is added to the existing storage of the reservoir, and in case that the resulting storage is greater than the maximum capacity of the reservoir, water is driven down to the upper tank in order to generate energy. In that case, the local and linear hydraulic losses are defined, as described in Chapter 5. The surplus water, which is always less than the maximum capacity of the reservoir-upper tank route, is transferred to the upper tank through the Ano Proespera hydroelectric plant. If the transferred water is less than the minimum operation flow with of the Pelton turbine, then no hydropower is generated. The price of the generated energy due to spill has to be a fixed and low, otherwise the hydroelectric plant operator will have the incentive to let the spill happen in order to enter the market first, regardless of the energy auction's results. Hence, the energy price due to spill is set at 16-25 €/MWh and varies across different simulations of the market. At the end, the reservoir storage equals its net capacity and the transferred water is added in the existing storage of the upper reservoir. Finally, the water level of the reservoir is updated, using eq. (9).

Next, the irrigation takes place, by examining the ability of the existing storage of the reservoir to cover the associated needs. If not, then failure occurs and the proportion of irrigation demand failure is added in an adder which sums the total amount of water deficit for irrigation.

Then, the reservoir level is updated using eq. (9). In addition, the completeness of the reservoir and the tanks are defined as a ratio between its storage and its maximum capacity. Concurrently, the amount of water that is owned by the wind park operator and the autonomous power station operator are defined in an attempt to determine a crucial factor of the configuration of the players' offers.

The hours during which the energy auction takes place are defined through the integral division of the time step with the total hours of each day, i.e. 24. After that, the energy auction starts.

The first step is to make a wind speed prediction for lead time of 12 to 36 hours ahead, i.e. the next day. When the SPARTA forecasting procedure is used, the number of realizations of the forecasted wind speed has to be defined. The larger the number of sets, the less is the bias of the forecasting model. If the meteorological forecasting procedure is used, then the forecasted wind speed equals to the observed one either increased or reduced by 5%, since the accuracy of this procedure is empirically estimated at about 95%. The accuracy of the energy demand forecast is set at 98%.

Following, using the forecasted wind speed data, the wind farm forecasted energy generation is employed. The hourly wind speed data is used as input at the power curve (Figure 26) to define the amount of produced energy. For the display of the generation of the Stravokoundoura wind farm, the result is being multiplied by the number of the wind turbines, while for the display of the standalone Perdiki wind turbine, the result is being multiplied by (600/900), in order to approximate the generation of energy through the associated wind turbine of 600 kW.

Knowing the predictions for energy demand and generation and the corresponding energy storage, the three energy players make their offers regarding the energy profile of the following day.

The offer of the wind park operator accounts for the forecasted energy and aims at least to the depreciation of the investment. In particular, for every one of the ten energy levels of the auction:

- If the forecasted energy generation exceeds the demand, or if it is slightly lower but the water storage of the wind park exceeds 10.000 m^3, which accounts for about 2,60 MWh, then the wind park's offer is set at 75 €/MWh.
- If the forecasted energy demand exceeds the forecasted generation for less than 100 kWh, while the water storage of the wind park exceeds 20.000 m^3, the offer of the wind park is set at 75 €/MWh, which is expected to be higher than the one of the hydroelectric power station and lower than the offer of the autonomous power station.
- If the forecasted energy generation is notably lower than the associated demand, the wind park makes an offer high enough so that it will not enter the energy market at all. It is expected that if the wind park operator sells its energy at approximately 50 €/MWh, then the investment will be depreciated.

In general, we argue that the wind park makes the most antagonistic offers.

The determination of the hydroelectric power plant's offer is much more complex. In most cases, its offers are higher than the ones of the wind park. In particular, the criteria accounted for are the completeness of the reservoir and the upper tank and the month that the auction refers to, due to the reservoir's seasonal restrictions.

If the auction takes place from October to February, when the minimum allowable water level is the lowest one, as set by PPC SA, while either the completeness of the upper tank and the reservoir exceed 75% and 90%, respectively, then the offer of the hydroelectric station for the first three energy levels is set to 70 €/MWh, even lower than the lowest offer of the wind park. Using this strategy the hydroelectric station aims in entering the market first and gaining from the surplus of energy provided the other two players, through pumped-storage and is implemented approximately 24% of the simulated time. Nevertheless, the conditions set are strict, because there is a high chance of failure, leading to paying costly penalties. Moreover, in this case the offers for the next four energy spaces are set at 90 €/MWh, while the last one is high enough so that it will not enter the energy market at all.

During the transitional months of March and April, if the completeness of the upper tank and the completeness of the reservoir are both above 90%, the offer of the hydroelectric power station for the first two energy spaces is set equal to 70 €/MWh, the one for the next five is 90 €/MWh and the last two are high enough so that it will not enter the energy market.

If the aforementioned conditions are not feasible during the winter season, and the completeness of the upper tank is above 40%, then the hydroelectric power station offers for the four first energy levels 90 €/MWh and extremely high prices for the other ones.

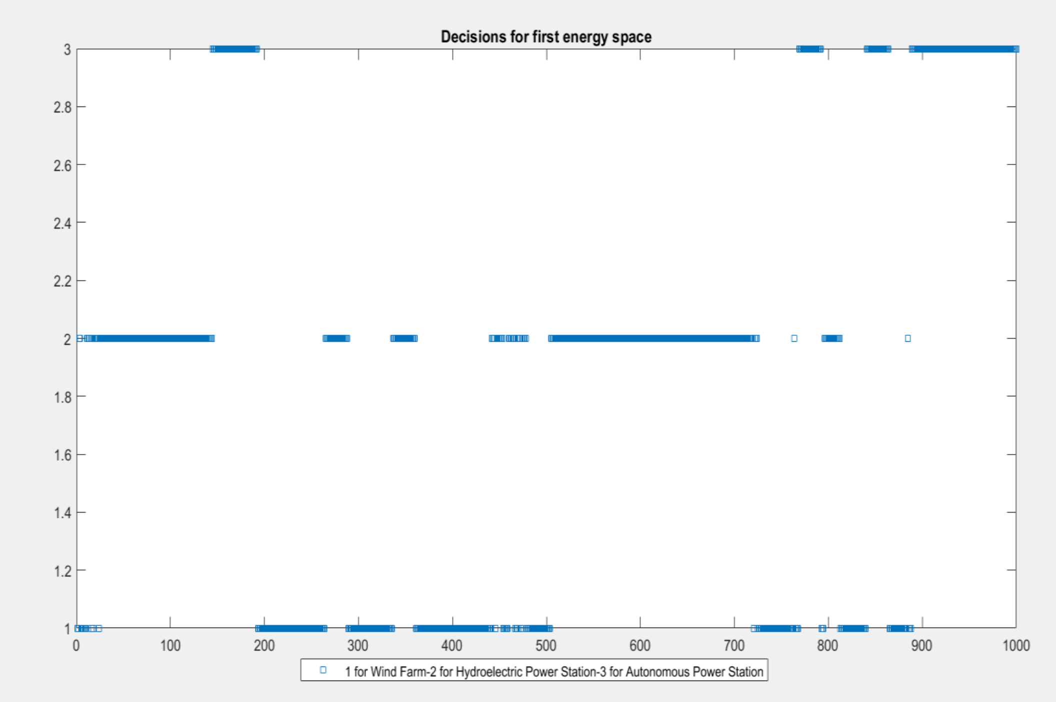
During the summer months, when the irrigation needs are large and the seasonal restrictions do not allow energy generation from the Ano Proespera power station, if the completeness of the upper tank is above 40%, the offer of the hydroelectric station for the four first energy spaces is 90 €/MWh and extremely high prices for the other ones. Otherwise, the hydroelectric station stays out of the market.

The above empirical procedure regarding the offers made by the wind park and the hydroelectric station came in an attempt to define market equilibrium. These values may vary during the different simulations of the hybrid energy system.

The offer of the autonomous power station is notably higher than the ones made by the other two players, due to the cost of the oil transport and environmental taxes. Specifically, in every time step and energy level this equals 350 €/MWh. The main role of the autonomous power station is to cover the deficits, thus maintaining the energy generation reliability at 100%. In other words, even though the majority of the other two players' offers are by far more antagonistic, when the hydroelectric power station has no storage to use for energy generation and the wind speed is either low or extremely high, the autonomous station has the chance to offer energy at the highest acceptable price. In addition to this, given the low response time of the station, it is used to cover deficits that have not been predicted.

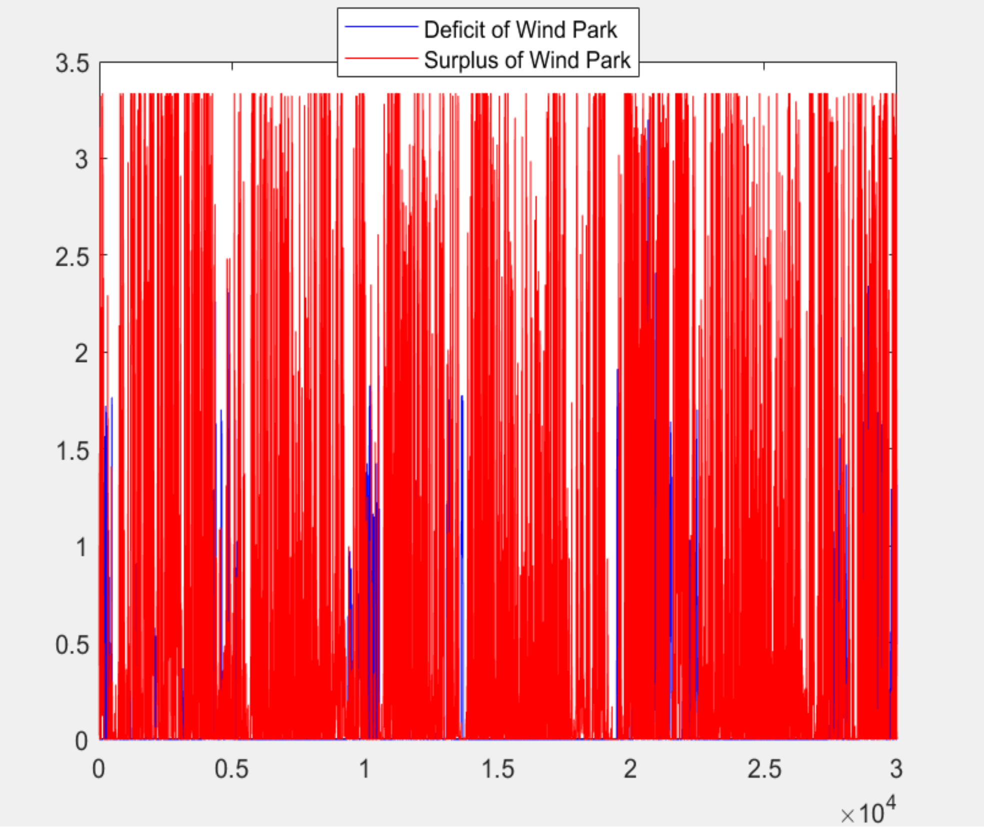
Then, the offers of the three players are compared, and the lowest one enters the market for each given energy level. As a result, a 10×24 table is created, referring to every hour of the day. The next step is the definition of the agreed earnings for every energy player. In particular, the amount of energy that every player agreed to is multiplied by each guaranteed price. Consequently, the earnings of each player for the next day are defined, given that they manage to provide the guaranteed energy.

In 22% of simulated time the wind park enters the market first, while this percentage for the hydroelectric power station is 37% and for the autonomous power station 41%. In Graph 37, a simulation of the decisions for the first energy space of one third of MWh for 5.000 hours is shown.



GRAPH 37: DECISIONS REGARDING THE FIRST ENERGY LEVEL FOR 5.000 HOURS

After the energy auction is completed, the real-time energy generation proceeds. At first, the water storage of the wind park is converted to potential energy storage using eq. (10). Then, the hourly wind data is used to define the amount of energy produced, as described before. Also, the percentage of the energy demand that it is to be covered by the wind park operation is defined. If the wind energy generation is greater than the guaranteed amount of energy the wind park would provide (not the energy demand apparently), then surplus of energy occurs. Otherwise, the deficit that is created will be encountered by either the hydroelectric power station or the autonomous power station. In case that this occurs during one of the winter season months in which the minimum allowable water level is the lowest one, i.e. October to April, and the completeness of the reservoir is above its minimum allowable level or in case that the completeness of the upper tank is above 60%, then the unexpected deficit made by the wind speed forecasting failure is encountered by the hydroelectric power station. Otherwise, the autonomous power station enters the market to cover the deficit. Since the response time is really low and the two power players have to generate more energy than agreed to, the prices paid are much higher. Specifically, the one for the hydroelectric power station is set at 300 €/MWh and for the autonomous power station at 500 €/MWh. Hence, this procedure increases drastically the power price of the island and highlights the need for trustworthy forecasting.



GRAPH 38: SIMULATION OF DEFICITS AND SURPLUSES BY THE WIND PARK FOR 30.000 HOURS

At the end, the total deficit is calculated as a sum between the energy that was not undertaken by the wind park plus the deficit that its miscalculations created. In addition to this, its surplus of energy, which occurs almost 32% of the simulation hours, is defined. It is possible that deficit and surplus of energy occur at the same time step: in case that the energy that the wind park agreed to provide is less than the energy it generated and simultaneously less than the demand of energy. This case occurs with a frequency of 24%. In Graph 38, the deficits and surpluses of the wind farm for 30.000 hours are presented.

Next, the seasonal restrictions of the reservoir are defined for the simulating time step, as set by PPC SA. Next, the reservoir level is calculated using eq. (9).

Afterwards, if deficit occurs the procedure continues with the simulation of the hydro turbines and the autonomous power station. The selection of either the reservoir-upper tank route or the upper tank-lower tank one depends on the completeness of the reservoir and the tank, and on the seasonal restrictions. During the winter period and if the reservoir level of the is above the minimum allowed and the completeness of the upper tank is less than the one of the lower tank or below 5%, the reservoir-upper tank route is selected. Otherwise, energy is generated through the upper tank-lower tank route, especially during the summer months.

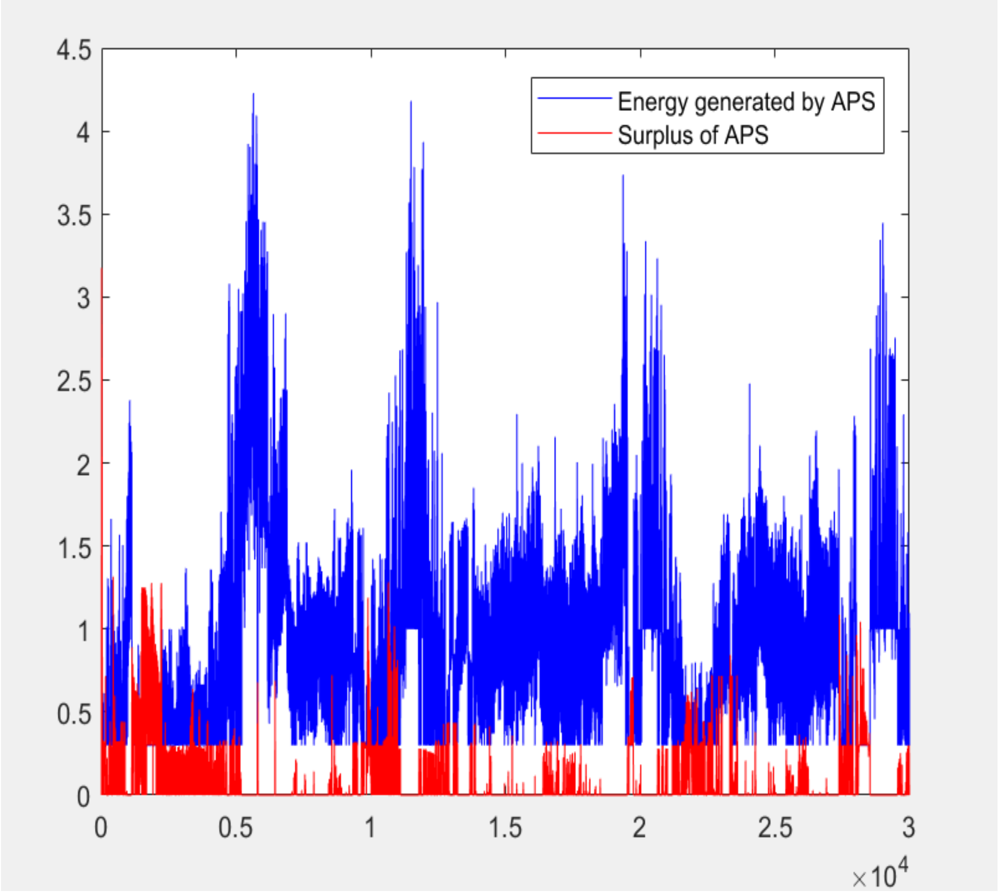
If the reservoir-upper tank route is selected for energy generation, first the discharge is calculated using eq. (13). As deficit, the total amount of energy that the hydroelectric power station has agreed to generate is put into the equation. The discharge cannot exceed the maximum reservoir-upper tank's capacity and the existing storage of the reservoir. Simultaneously, the discharge should be high enough so that the hydro turbine has the ability to operate. In case of small-scale deficits and due to the existence of the minimum discharge with which the Pelton hydro turbine can produce hydro power, larger amounts of water are released, and as a result more water is transported to lower levels for the need of deficit coverage.

Next, by applying eq. (12) and calculating the flow velocity, linear and local hydraulic losses are defined. Given that, using eq. (10) the water to be released into in order to generate energy equal to the deficit is calculated. This amount does not exceed the existing storage and the maximum capacity of the turbines.

If the released water is less than the minimum operational flow of the turbine, no energy is generated and the deficit is covered by the autonomous power station at the price of 500 €/MWh. If the available storage or turbine capacity limit the energy generation in quantities less than the existing deficit, then the generated energy is injected to the energy grid, and the remaining deficit is covered by the autonomous power station.

Next, the total energy generation by the hydroelectric power station is calculated using eq. (10). If this is less than the amount agreed to, then a penalty of 160 €/MWh is implemented, while if it is larger, then the price paid for the additional energy is 400 €/MWh.

The amount of energy generation by the autonomous power station is increased due to storage deficit in the reservoir. If the total energy generation of the autonomous power station is more than the amount agreed to and above the minimum power of 300 KWh, then the price paid for the extra energy is 350 €/MWh. In case that the energy generation of the autonomous power station is above 300 kWh and does not enter the grid, then surplus owned by the autonomous power station is created. In Graph 39, the energy generation and surpluses of the autonomous power station for 30.000 hours are presented.



GRAPH 39: TIME SERIES OF ENERGY GENERATION AND SURPLUSES BY THE APS FOR 30.000 HOURS

Following, the transported water is removed from the reservoir storage and added to the storage of the upper tank.

If the upper tank-lower tank route is selected, the discharge is calculated using eq. (13). The deficit consists of the total amount of energy that the hydroelectric power station has agreed to generate plus the deficit of the wind park plus the amount of energy exceeding 300 kWh the autonomous power station agreed to provide, given that the last two have available storage at the upper tank. The discharge cannot exceed the maximum capacity of the upper tank-lower tank route and the existing storage of the upper tank. This discharge has to be large enough so that the hydro turbine has the ability to operate and produce energy.

By applying eq. (12) and defining the flow velocity, linear and local hydraulic losses are calculated. Next, using eq. (10) the total amount of water to be released into the turbine in order to generate energy equal to the deficit is calculated. This amount cannot exceed the existing storage and the maximum capacity of the turbines.

If the released water is less than the minimum operation flow of the turbine, no energy is generated and the deficit is covered by the autonomous power station at the price of 500 €/MWh. If the available storage or turbine capacity limit the energy generation in quantities less than the existing deficit, then the generated energy is injected to the energy grid, and the autonomous power station is forced to cover the remaining deficit.

Following, the total amount of energy generation by the hydroelectric power station is calculated using eq. (10). If the latter is less than the agreed quantity, a penalty of 160 €/MWh is set, otherwise the price paid for the extra energy is 400 €/MWh.

If the total energy generation of the autonomous power station is more than the amount agreed to and above the minimum power of 300 KWh, then the price paid for the extra energy is 350 €/MWh. If the energy generation of the autonomous power station is above 300 kWh and its energy does not enter the grid, then surplus owned by the autonomous power station is created.

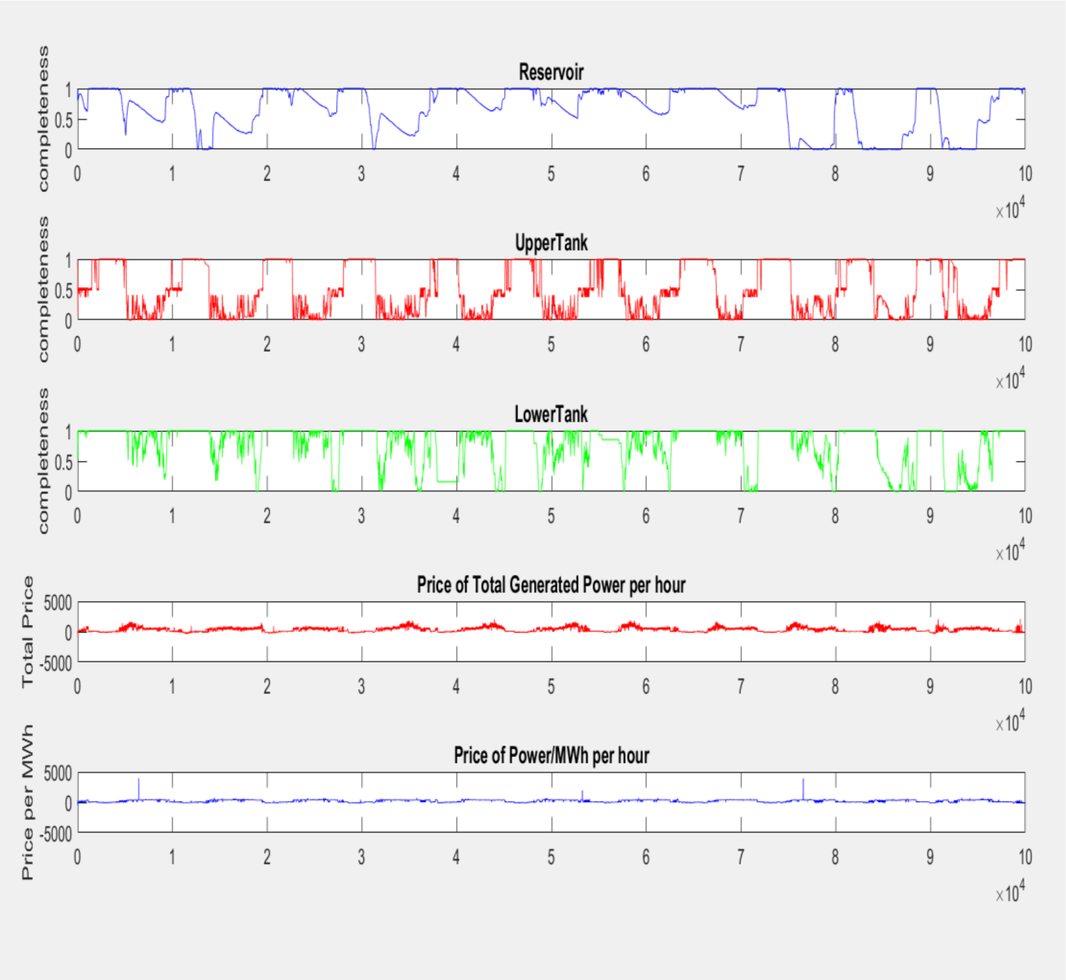
Next, the transported amount of water is removed from the upper tank and added to the lower one.

The sum of payments of the three energy players during the above procedure minus the penalties paid by them defines the price of power for the simulated hour. By dividing this value by the energy demand of the time step, the power price per MWh for the simulated hour is calculated. In Graph 40, a time series of the completeness of the reservoir and the tanks and the power price at each time are shown.

Following, the reservoir level is updated using eq. (9). Moreover, the completeness of the reservoir and the tanks are defined as a ratio of its storage to its capacity.

If either the energy surplus owned by the wind park or one owned by the autonomous power station occurs, the water pumping process takes place.

The discharge is calculated using eq. (14). As surplus, the sum of the surplus of the wind park and the autonomous power station is used. The discharge cannot exceed the maximum capacity of the pumping station and the existing storage of the lower tank. Then, by calculating the energy gradient and the flow velocity, linear and local hydraulic losses are defined and by using eq. (10) the total amount of water that can be pumped into the upper tank is computed. This amount cannot exceed the existing storage of the lower tank and the maximum capacity of the pumping station.

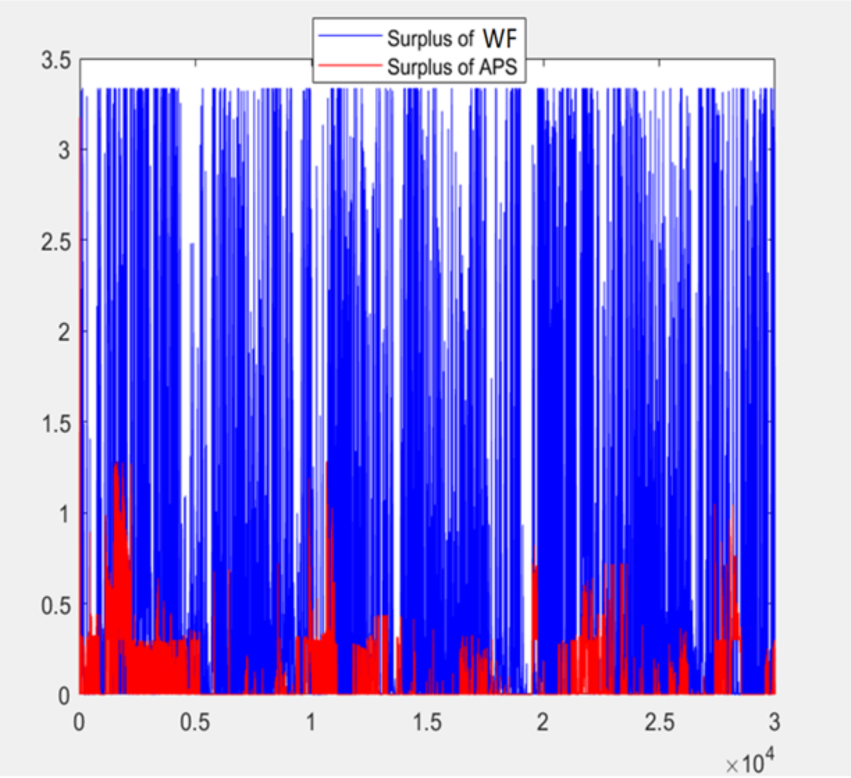


GRAPH 40: TIME SERIES OF COMPLETENESS OF THE RESERVOIR, THE TANKS AND THE POWER PRICE FOR 100.000 HOURS

Next, the total amount of stored energy is calculated and the transported water is removed from the lower tank and added to the upper one. If the total stored energy equals to the sum of the energy surplus of the wind park and the autonomous power station, then the property of the stored amount of water is separated accordingly. If not, then the property is defined by the ratio of the surplus of each energy player to the total energy stored by the pumped water to the upper tank.

It is decided that the maximum storage capacity that the hydroelectric power station provides to the other two energy players is varying according to the month of the simulation. In particular, during the summer months, due to high water needs, only 10.000 m^3 can be offered for energy storage. Between October and February, this limit increases to 40.000 m^3, while for March and April the maximum water storage offered is 24.000 m^3.

In Graph 41, the surpluses of the wind park and the autonomous power station for 30.000 hours are presented.



GRAPH 41: TIME SERIES OF ENERGY SURPLUSES BY THE WIND PARK AND THE AUTONOMOUS POWER STATION FOR 30.000 HOURS

At the end of each step, three counters estimate the time steps during which the reservoir and the two tanks are empty. After that, the counters are divided by the total number of simulation hours in order to express the percentage of times that either the reservoir or the tanks have no storage during the simulation.

At the end of the simulation the following quantities are computed:

- irrigation failure, as the ratio of the counter of irrigation failure to the total hours of simulation;
- irrigation resilience, as the ratio of the maximum times of consecutive irrigation failure to the counter of irrigation failure;
- irrigation vulnerability, as the ratio of the sum of the total amount of water that the irrigation system was short of to the number of irrigation failures;
- the percentage of time that the reservoir and the tanks are empty;
- the earnings of the wind park operator, the hydroelectric power plant and reservoir operator and the autonomous power station operator;
- the earnings of irrigation;
- the mean value of power price.

In conclusion, this procedure employs the internal function of the hybrid system featuring the operation of a daily energy market. The management models of the hybrid system are differentiated on factors relating to the options and capabilities. These management models are presented and compared in the next section in an attempt to define the optimal one.

SIMULATION OF DIFFERENT MANAGEMENT MODELS

So far, we described the market's operation under specific operation rules. By changing these rules, we get significantly dissimilar outcomes. The most critical factors that define the alternative management policies are the pricing model of the power generation, the forecasting procedure used for the prediction of the wind speed during the energy auction and the structure of the energy market.

First of all, we will examine which one of the aforementioned pricing models leads to lower power price, given that it provides balanced earnings for all the power players. Secondly, the predictive capacity of the simulation model is of high importance, as poor forecasting of wind speeds would lead to a large number of deficits. Finally, the determination of the proper surplus management model is also of high importance.

In conclusion, the impacts of these factors on the system behavior and especially on the power price will be examined and compared by employing simulations for several different management policies.

SIMULATION NO.1

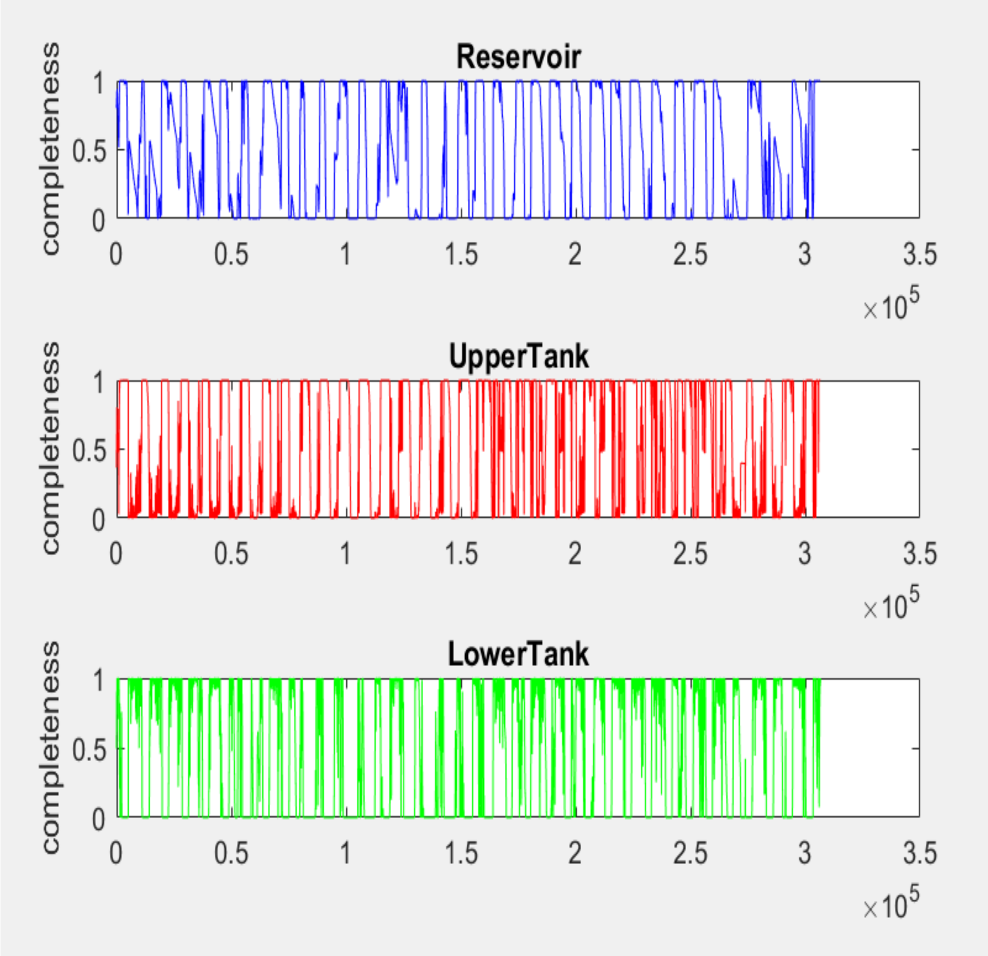
Simulation No.1 aims at representing the operation of the hybrid energy system featuring the "guaranteed price" pricing model for each energy player. In particular, the wind park generation is priced at 84,6 €/MWh, as set in Table 1, and the hydroelectric power station at 295 €/MWh. The autonomous power station is used to cover the deficits the other two producers create and is priced at 350 €/MWh.

The criteria for deciding the proper route for energy generation are the following: Between October and April, if the completeness of the reservoir is higher than the limit set by the seasonal restrictions, while the storage of the upper tank is lower than the one of the lower tank, or the completeness of the upper tank is below 5%, then the reservoir-upper tank route is selected for energy generation; otherwise the upper tank-lower tank one is used. As a result, the reservoir-upper tank route is chosen about 34% of time in which deficits occurred, while 66% of time energy is generated by releasing water from the upper tank. Regarding energy storage, given that water cannot be pumped into the reservoir, the only way to store energy surpluses is the lower tank-upper tank route.

The final results of the simulation were:

- Irrigation Reliability = 93,2%
- Irrigation Resilience = 0,005%
- Irrigation Vulnerability = 112,5 m^3

In Graph 42, the time series of storage completeness of the reservoir, the upper tank and the lower tank are presented. The reservoir remains empty 22,9% of time, the upper tank 24,5% and the lower tank 41,9%.



GRAPH 42: TIME SERIES OF COMPLETENESS OF THE RESERVOIR AND THE TANKS FOR SIMULATION NO.1

The mean value of wind energy generation is 0,72 MWh, with standard deviation 1,1 MWh, while in 22,4% of the time steps energy was generated due to spill of the reservoir with mean value of 0,81 MWh per operating time step. The mean value of the hydroelectric energy generation is 1,14 MWh per operating hour.

During the operation, 50,7% of annual energy is generated from the wind park (6,23 GWh), 28,9% from the hydroelectric stations and the rest by the autonomous power station. The wind park operator earns approximately 527.000 €/year, the hydroelectric power station 1.385.000 €/year and the autonomous power station 1.175.000 €/year. The earnings due to irrigation are 22.000 €/year. Concurrently, the mean power price is estimated at 276 €/MWh. It is noted that if only the autonomous power station was used for energy production, as made in several non-interconnected Greek islands, the mean power price would be 350 €/MWh.

SIMULATION NO.2

Simulation No.2 represents the energy market featuring the SPARTA forecasting model using five realizations during each forecasting procedure, a pricing model based on discrimination, a Limit Price System pricing model and the renting of water from the hydroelectric station to the wind park and the autonomous power station.

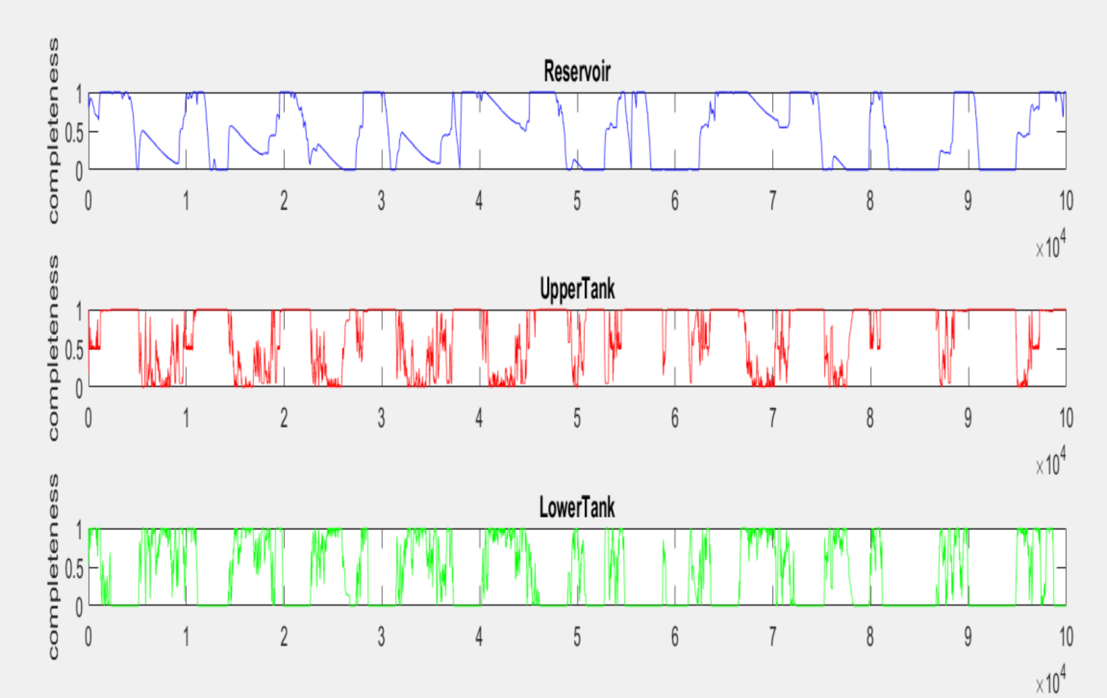
The criteria for deciding the proper route for energy generation are the following: Between October and April, if the completeness of the reservoir is higher than the limit set by the seasonal restrictions, while the storage of the upper tank is lower than the one of the lower tank, or the completeness of the upper tank is below 5%, then the reservoir-upper tank route is selected for energy generation; otherwise the upper tank-lower tank one is used.

The final results of the simulation were:

- Irrigation Reliability = 82,7%
- Irrigation Resilience =0,005 %
- Irrigation Vulnerability = 92 m^3

Graph 43 presents the time series of storage completeness of the reservoir, the upper tank and the lower tank. The reservoir remains empty 18,7% of time, the upper tank 2,1% and the lower tank 45,5%.

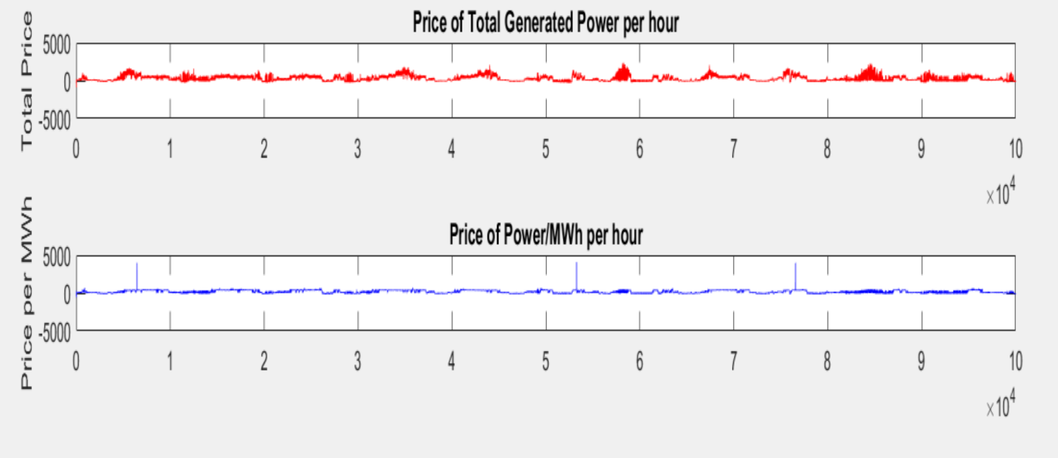
The mean value of wind energy generation is 0,72 MWh, with standard deviation approximately 1,1 MWh. In 21,7% of the time steps energy was generated due to spill of the reservoir with mean value of 0,90 MWh per operating time step. Concurrently, the mean value of energy generation was 0,32 MWh per hour for the hydroelectric power station and 0,88 MWh for the autonomous power station.



GRAPH 43: TIME SERIES OF COMPLETENESS OF THE RESERVOIR AND THE TANKS FOR SIMULATION NO.2

The wind park operator earns 651.000 €/year, the hydroelectric power station 791.000 €/year and the autonomous power station 825.000 €/year. The simulation assumes that the wind park operator rents water from the upper tank at the price of 2 €/m³ (which is quite low, in order to confront stochasticity), while the autonomous power station rents at 20 €/m³. The mean losses due to irrigation are 52.730 €/year. Concurrently, the mean power price is estimated at approximately 168,8 €/MWh, while if the Limit Price System was used it is about 204,3 €/MWh.

Graph 44 shows the mean power price per hour and per MWh of the simulation.



GRAPH 44: TIME SERIES OF POWER PRICE FOR SIMULATION NO.2

SIMULATION NO.3

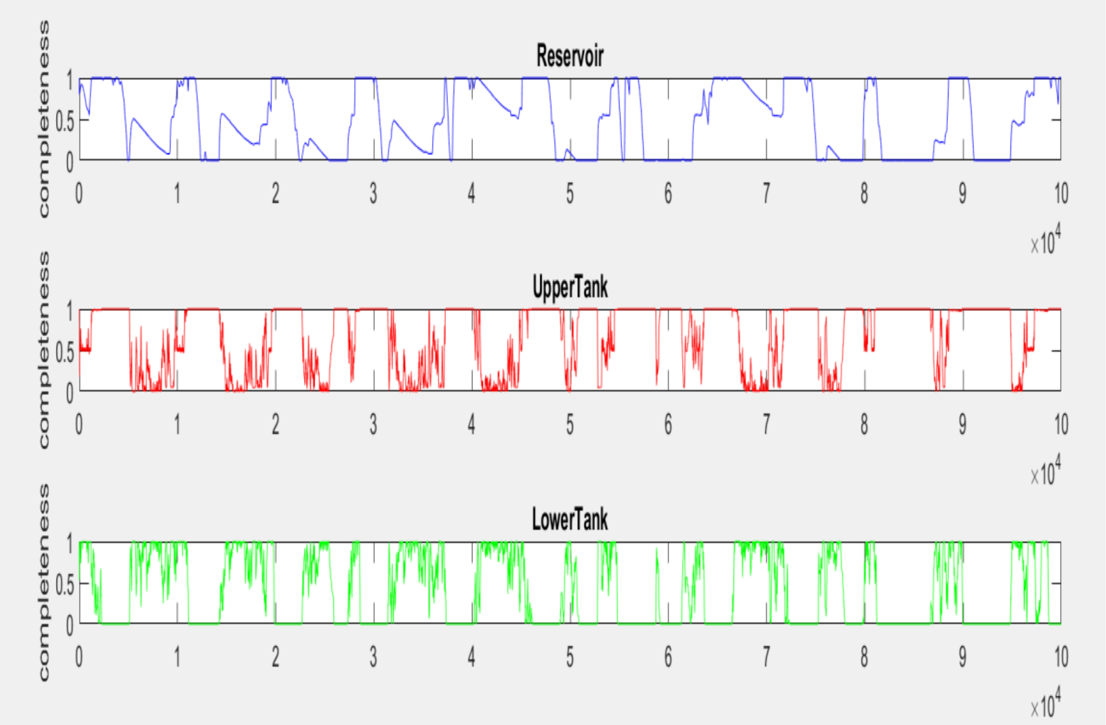
Simulation No.3 represents the energy market featuring the SPARTA forecasting model using ten realizations during each forecasting procedure, a pricing model based on discrimination, a Limit Price System pricing model and the purchase of the energy surpluses from the hydroelectric power station.

The criteria for deciding the proper route for energy generation are the following: Between October and April, if the completeness of the reservoir is higher than the limit set by the seasonal restrictions, while the storage of the upper tank is lower than the one of the lower tank, or the completeness of the upper tank is below 5%, then the reservoir-upper tank route is selected for energy generation; otherwise the upper tank-lower tank one is used.

The final results of the simulation were:

- Irrigation Reliability = 82,1%
- Irrigation Resilience = 0,006%
- Irrigation Vulnerability = 88,7 m^3

Graph 45 presents the time series of storage completeness of the reservoir, the upper tank and the lower tank. The reservoir remains empty 20,3% of time, the upper tank 2% and the lower tank 46,4%.

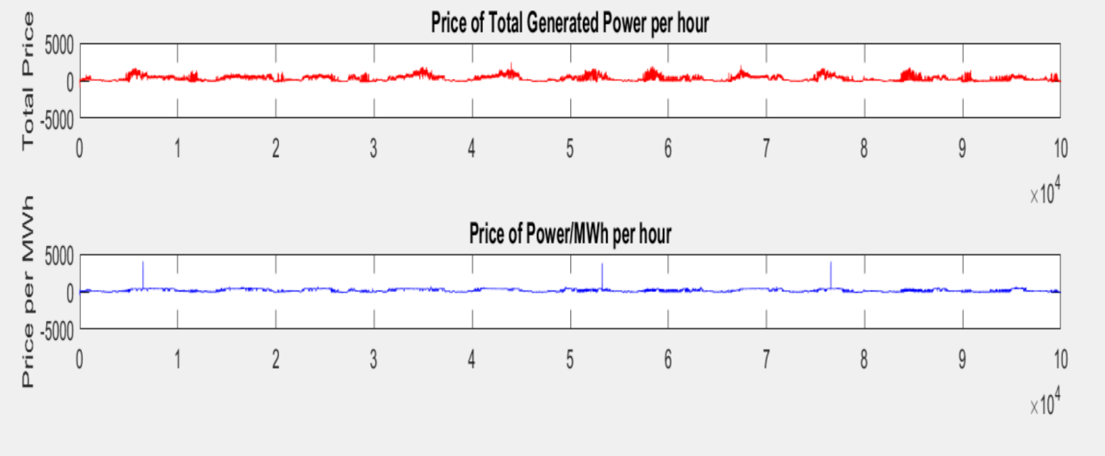


GRAPH 45: TIME SERIES OF COMPLETENESS OF THE RESERVOIR AND THE TWO TANKS FOR SIMULATION NO.3

The mean value of wind energy generation is 0,72 MWh, with standard deviation approximately 1,1 MWh. In 21% of the time steps energy was generated due to spill of the reservoir with mean value of 0,86 MWh per operating time step. The mean value of energy generation was 0,47 MWh per operating hour for the hydroelectric power station and 0,90 MWh for the autonomous power station.

The wind park operator earns approximately 111.000 €/year, the hydroelectric power station about 538.000 €/year and the autonomous power station 1.566.000 €/year. The losses due to irrigation are about 52.240 €/year. Concurrently, the mean power price is estimated at approximately 155,7 €/MWh, while if the Limit Price System was used it would be about 190 €/MWh.

Graph 46 shows the mean power price per hour and per MWh of the simulation.



GRAPH 46: TIME SERIES OF POWER PRICE FOR SIMULATION NO.3

SIMULATION NO.4

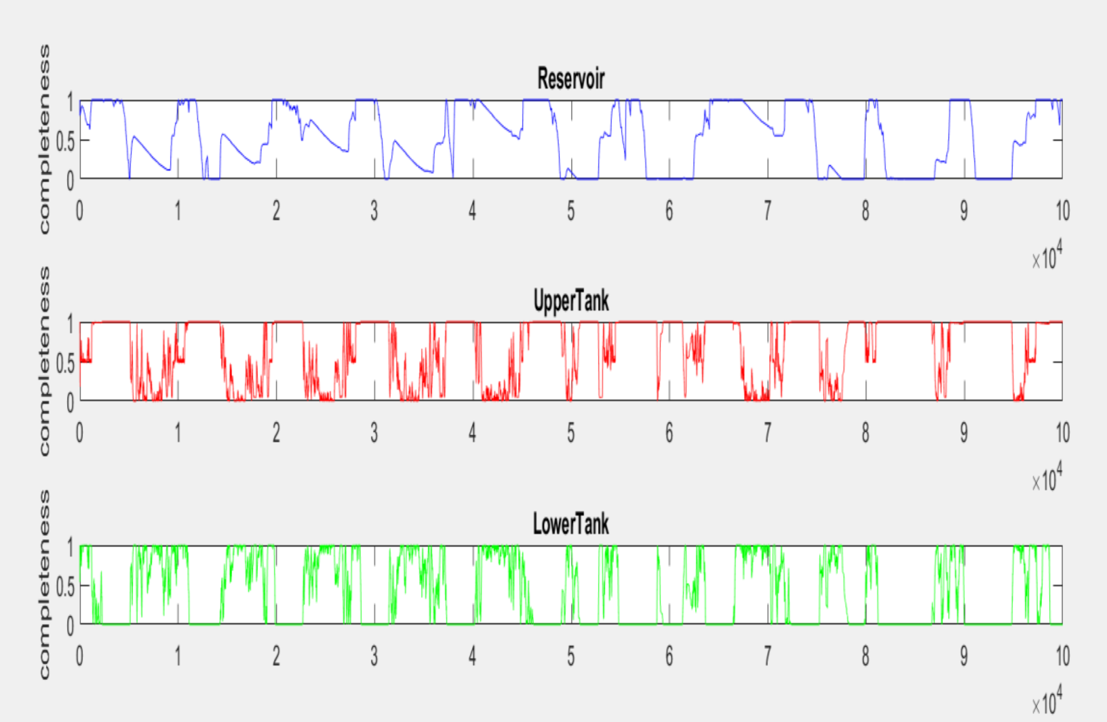
Simulation No.4 represents the energy market featuring a pricing model based on discrimination, a Limit Price System pricing model and the renting of water from the hydroelectric power station to the wind park and the autonomous power station. The forecasting process is assumed that predicts wind speeds with 95% accuracy.

The criteria for deciding the proper route for energy generation are the following: Between October and April, if the completeness of the reservoir is higher than the limit set by the seasonal restrictions, while the storage of the upper tank is lower than the one of the lower tank, or the completeness of the upper tank is below 5%, then the reservoir-upper tank route is selected for energy generation; otherwise the upper tank-lower tank one is used.

The final results of the simulation were:

- Irrigation Reliability = 85%
- Irrigation Resilience = 0,006%
- Irrigation Vulnerability = 95 m^3

Graph 47 presents the time series of storage completeness of the reservoir, the upper tank and the lower tank. The reservoir remains empty 16,7% of time, the upper tank 2,1% and the lower tank 44,8%.

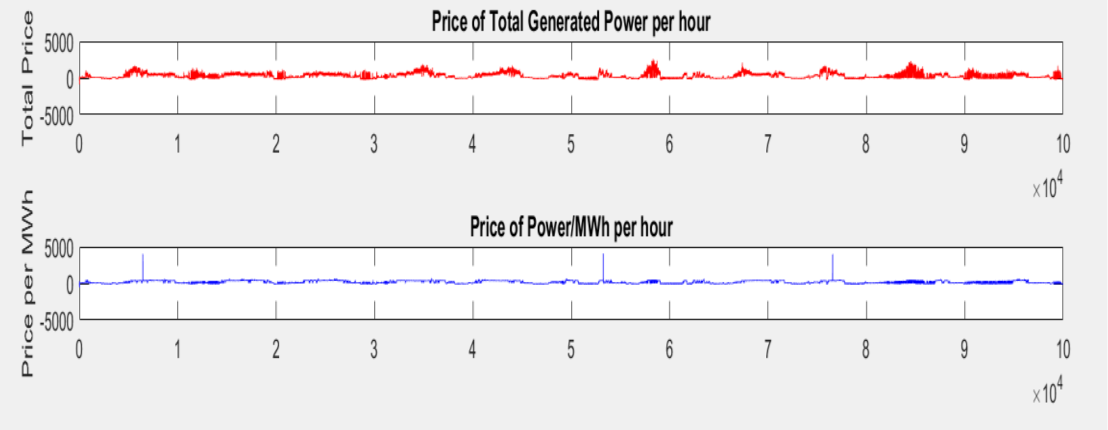


GRAPH 47: TIME SERIES OF COMPLETENESS OF THE RESERVOIR AND THE TANKS FOR SIMULATION NO.4

The mean value of wind energy generation is 0,72 MWh, with standard deviation approximately 1,1 MWh. In 21,9% of the time steps energy was generated due to spill of the reservoir with mean value of 0,90 MWh per operating time step. The mean value of energy generation was 0,33 MWh per operating hour for the hydroelectric power station and 0,86 MWh for the autonomous power station.

The wind park operator earns approximately 615.000 €/year, the hydroelectric power station about 791.000 €/year and the autonomous power station 824.000 €/year. The simulation assumes that the wind park operator rents water from the upper tank at the price of 2 €/m^3 (which is quite low, in order to confront stochasticity), while the autonomous power station rents at 20 €/m^3. The losses due to irrigation are about 46.590 €/year. Concurrently, the mean power price is estimated at approximately 165 €/MWh, while if the Limit Price System was used it would be about 194,9 €/MWh.

Graph 48 shows the mean power price per hour and per MWh of the simulation.



GRAPH 48: TIME SERIES OF POWER PRICE FOR SIMULATION NO.4

SIMULATION NO.5

Simulation No.5 represents the energy market featuring a pricing model based on discrimination, a Limit Price System pricing model and the purchase of the energy surpluses from the hydroelectric power station. The forecasting process is assumed that predicts wind speed up to 36 hours ahead with 95% accuracy.

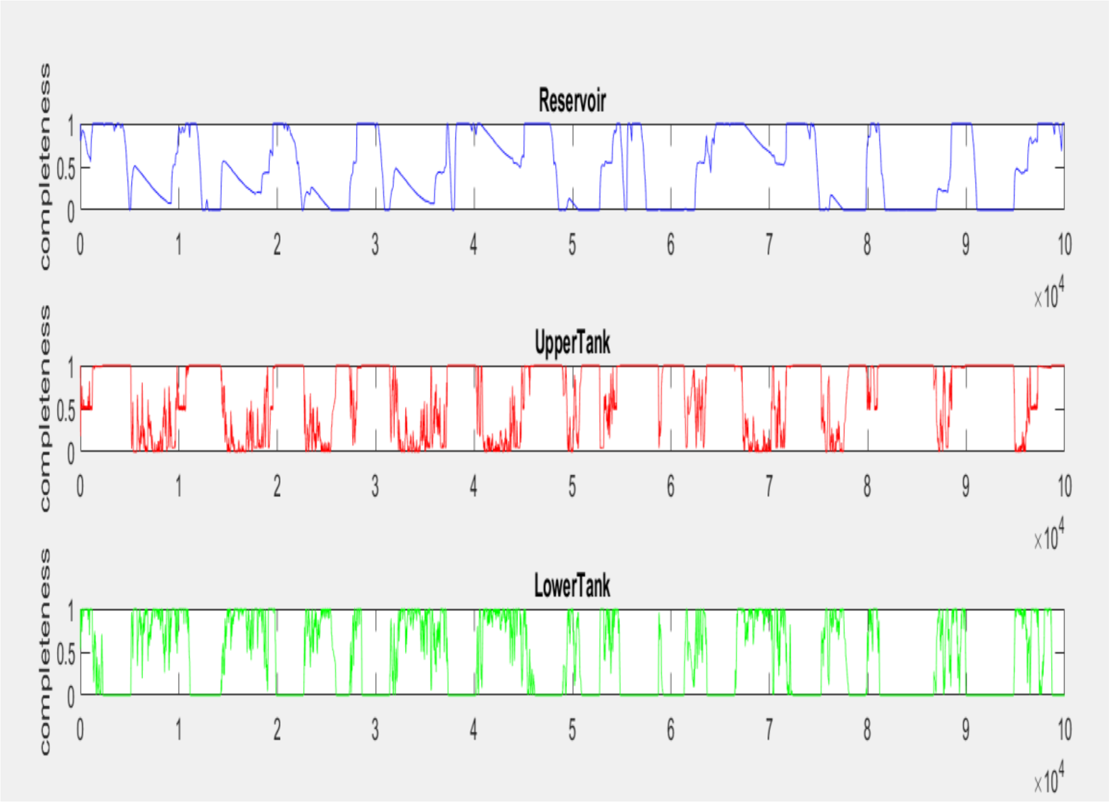
The criteria for deciding the proper route for energy generation are the following: Between October and April, if the completeness of the reservoir is higher than the limit set by the seasonal restrictions, while the storage of the upper tank is lower than the one of the lower tank, or the completeness of the upper tank is below 5%, then the reservoir-upper tank route is selected for energy generation; otherwise the upper tank-lower tank one is used.

The final results of the simulation were:

- Irrigation Reliability = 82,1%
- Irrigation Resilience = 0,006%
- Irrigation Vulnerability = 88,83 m^3

Graph 49 presents the time series of storage completeness of the reservoir, the upper tank and the lower tank. The reservoir remains empty 20,1% of time, the upper tank 2,1% and the lower tank 46%.

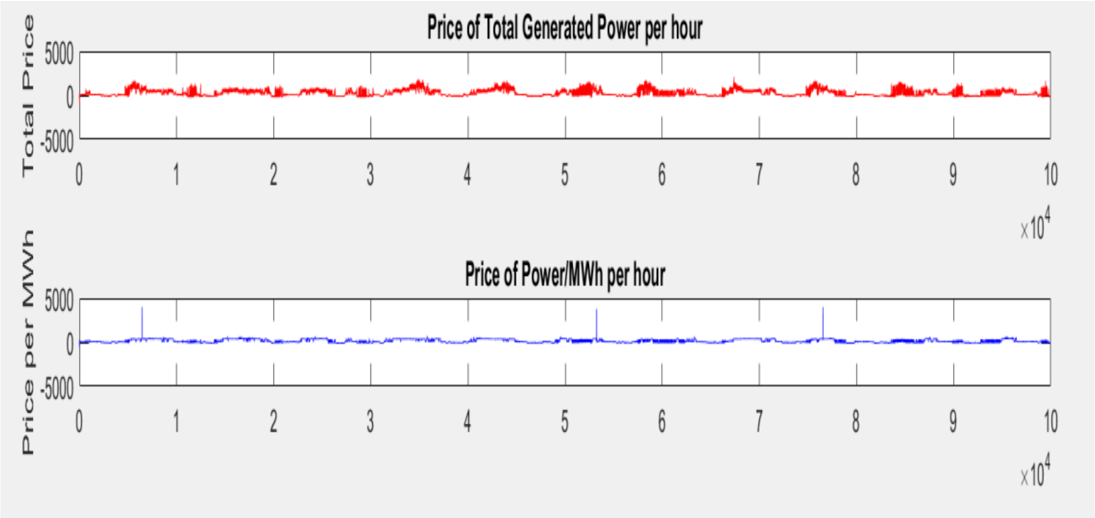
The mean value of wind energy generation is 0,72 MWh, with standard deviation approximately 1,1 MWh. In 21,2% of the time steps energy was generated due to spill of the reservoir with mean value of 0,89 MWh per operating time step. The mean value of energy generation was 0,47 MWh per operating hour for the hydroelectric station and 0,87 MWh for the autonomous power station.



GRAPH 49: TIME SERIES OF COMPLETENESS OF THE RESERVOIR AND THE TANKS FOR SIMULATION NO.5

The wind park operator earns approximately 1.413.700 €/year, the hydroelectric power station about 245.000 €/year and the autonomous power station 1.670.000 €/year. The losses due to irrigation are about 52.240 €/year. Concurrently, the mean power price is estimated at approximately 143,2 €/MWh, while if the Limit Price System was used it would be about 167,2 €/MWh.

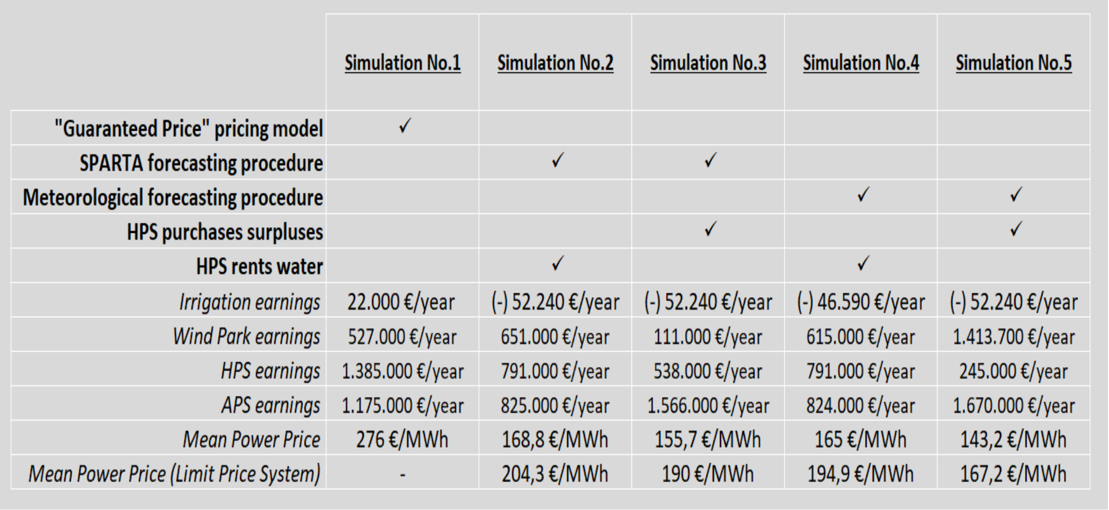
Graph 50 shows the mean power price per hour and per MWh of the simulation.



GRAPH 50: TIME SERIES OF POWER PRICE FOR SIMULATION NO.5

COMPARISON AND CONCLUSIONS

Table 5 summarizes the key outcomes of the five simulations, investigating the impacts of different forecasting procedures, pricing policies and surplus management practices.



	Simulation No.1	Simulation No.2	Simulation No.3	Simulation No.4	Simulation No.5
"Guaranteed Price" pricing model	✓				
SPARTA forecasting procedure		✓	✓		
Meteorological forecasting procedure				✓	✓
HPS purchases surpluses			✓		✓
HPS rents water		✓		✓	
Irrigation earnings	22.000 €/year	(-) 52.240 €/year	(-) 52.240 €/year	(-) 46.590 €/year	(-) 52.240 €/year
Wind Park earnings	527.000 €/year	651.000 €/year	111.000 €/year	615.000 €/year	1.413.700 €/year
HPS earnings	1.385.000 €/year	791.000 €/year	538.000 €/year	791.000 €/year	245.000 €/year
APS earnings	1.175.000 €/year	825.000 €/year	1.566.000 €/year	824.000 €/year	1.670.000 €/year
Mean Power Price	276 €/MWh	168,8 €/MWh	155,7 €/MWh	165 €/MWh	143,2 €/MWh
Mean Power Price (Limit Price System)	-	204,3 €/MWh	190 €/MWh	194,9 €/MWh	167,2 €/MWh

TABLE 5: AGGREGATED RESULTS OF DIFFERENT ENERGY MARKET SIMULATIONS

We conclude that the operation of an energy market with a pricing model based on discrimination provides an average power price 36-44% lower than the existing “guaranteed price” model. It also provides approximately 16-20% lower prices than the Limit Price System, without taking into account the possibility of the power players forming a cartel during the operation of a Limit Price System pricing model. Undoubtedly, the simulation of different management models of Ikaria’s energy market shows that a pricing model based on discrimination provides the lowest power prices of all, regardless of the other factors affecting the simulation.

The purchase of the energy surpluses of the wind park and the autonomous power station from the hydroelectric power station provides the lowest power prices of all, but the earnings of the power players are not equally spread.

Specifically, in Simulation No.3 the wind park earns only 111.000 €/year due to the penalties implied to deficits, because of the poor wind speed predictions. Hence, the depreciation of the wind park investment will last longer than the average lifetime of its wind turbines, which is about 20 years. As a result, the incentives for investing at a wind park would have been rescinded and the hybrid energy system would not have been made at the first place.

In addition, in Simulation No.5 the hydroelectric power station earns only 245.000 €/year and loses 52.240 €/year due to irrigation failure. Thus, the depreciation of the hydroelectric station investment would be completed at approximately 150 years.

On the contrary, renting water from the hydroelectric power station to the wind park and the autonomous power station provides about 10% higher power prices on average, but also ensures a fairer spread of earnings to the power players, leading to better incentives for investments on the island’s hybrid energy system.

In simulations No.2 and No.4 the depreciation of the wind park investment would have been made at approximately 8 years, leaving the rest years of the wind turbines’ lifetime to provide profits to the operator. Concurrently, the hydroelectric power station depreciates its investment at about 40 years.

Moreover, the results of the different simulations highlight the need for a procedure ensuring high wind speed forecasting accuracy. The earnings of the wind park in simulation No.5 are 140% higher than the ones in simulation No.3, which uses SPARTA as forecasting model. On the other hand, simulation No.4 that resembles the accuracy of meteorological forecasting provides lower power prices than simulation No.2, but similar earnings of the power players.

In brief, the simulation of the different management models provides several conclusions about the operation of the hybrid energy system. First, the operation of an energy market with a pricing model based on discrimination provides better power prices than the existing “guaranteed price” model and is also better than the Limit Price System. Secondly, the short-term wind speed projections should be account for meteorological forecasts. Thirdly, the operation of the energy market by the renting of water from the hydroelectric power station to the wind park and the autonomous power station provides higher power prices on average, but more equally spread earnings to the power players. All things considered, is can be concluded that simulation No.4 is the most representative of an optimal operation of the energy market.

CHAPTER 8: CONCLUSIONS AND FUTURE RESEARCH PERSPECTIVES

The aim of the NAERAS project is to produce energy through the combination of two different forms of RES, i.e. wind and hydroelectric, by storing the surplus of wind energy through pumping. This project is the second in the world and the evolution of operation of such hybrid energy systems will provide a credible response to the issue of storage and controlled distribution of clean energy production and the penetration of RES on the non-interconnected network.

First, we investigated the functionality of such a project in order to determine the hybrid energy system's characteristics to meet combined irrigation and energy generation demands. Furthermore, the sensitivity of the hybrid energy system to its components was examined in an attempt to define its optimal operation.

Secondly, via the energy market simulation we have drawn important conclusions about the possibility of establishing an optimal energy management policy to a non-interconnected network, by comparing the existing legislative framework with a more liberal management model. In particular, the existing "guaranteed price" pricing model was compared with a free market case study. Consequently, we evaluated the incentives to invest in RES units and optimal management to reduce the price of the supplied electricity.

CONCLUSIONS

Throughout the simulation of the hybrid energy system and its energy market, the following research objectives were attained:

- High exploitation of renewable energy production due to the flexibility offered by the hybrid system (in terms of storage of excess energy), which allows regulating the highly varying input meteorological drivers;
- Production of synthetic wind speed time series that represent the stochastic behavior of the observed processes;
- Configuring a suitable wind forecast model up to 36 hours ahead;
- Comparison of different simulations and determination of the optimal rules governing the hybrid energy system in an attempt to maximize the reliability of energy generation and abstractions for irrigation, while minimizing the average cost of electricity;
- Comparison of the existing "guaranteed price" model of RES with a more liberal management model.
- Comparison of different energy market simulations and determination of its optimal rules and fixed prices, in an attempt to minimize the cost of

electricity in the non-interconnected island, but also offering motivation for investments.

Moreover, the general conclusions regarding the rationale of hybrid energy systems, especially in the non-interconnected network, are:

- Determination of the level of exploitation of RES in small non-interconnected communities and finding solutions for improved RES penetration in the island energy system;
- Elimination of risks of energy deficits, at the same time ensuring energy production in lower prices than today (monopoly of diesel station);
- Fulfillment of irrigation demand with high reliability;
- Description of the hybrid energy system’s operation;
- Description of the energy market’s operation;
- Determination of the structure of a hypothetical energy market on a non-interconnected island;
- Determination of the optimal surplus management model through the operation of the energy market;
- Restricting the possibility of energy players forming a cartel.

The particular conclusions from the modelling of Ikaria’s hybrid energy system and its energy market are:

- Reduction of pollutants emitted by 13,800 tons per year;
- Awareness that the seasonal restrictions of the hybrid energy system not only improves the coverage of irrigation, but also increases the reliability of energy production;
- Determination of the mean power price of Ikaria using the existing pricing model;
- Presentation of the possibility of optimization of the hybrid energy system and the its sensitivity to major characteristics, i.e. reservoir and tank storage capacities, pumping station nominal power and minimum hydro-turbine discharge;
- Investigation of the possibility of reducing the price of energy offered on a non-interconnected island;
- Addressing the monopoly status of energy production from the existing oil station;
- Simulation of a three-player energy stock, by preserving the associated governing rules and determining the criteria of the configuration of each player’s offer;

- Optimization of the energy market’s fixed prices in an attempt to achieve reasonable profits for all counterparties, while reducing the average price of electricity;
- Comparison of the existing “guaranteed price” pricing model, as set by PPC SA, the existing Limit Price System for the operation of energy stocks and a pricing model based on discrimination;
- Determination of an energy market operation which results to a 36,6% lower power price than the one provided by the existing pricing model and simultaneously enables the opportunity for depreciation of the energy players’ investments.

FUTURE RESEARCH PERSPECTIVES

From the experience gained so far we also detected several issues for future research, regarding the operation of the hybrid energy system. Specifically:

- Improving wind velocity forecasts by coupling stochastic and deterministic approaches;
- In case a more accurate forecasting model is to be developed, the intra-daily energy auction can be simulated;
- Investigating the possibility of larger RES penetration (plans for a PV station of 1,04 MW are already being discussed) and simulating the energy stock with more than three energy players;
- Adjusting the model to a finer temporal scale, i.e. 5 min, thus taking into account the turbulent character of wind energy, which forces the wind energy generation not to enter the grid immediately, thus favoring the use of a double pipeline of the hydroelectric power station;
- Investigating different structures of the energy stock;
- Optimizing the components and especially the fixed values set for the operation of the energy market;
- Investigating the possibility of the connection of the island with the domestic network and evaluation of this investment.

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