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Diploma Thesis

Multicriteria evaluation of historical reforms in electricity components across Europe

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Abstract

The electricity domain in Europe has undergone significant changes during the last 30 years. The technological advancements of the last decades in the sector have introduced new and effective methods of electricity production, and renewable sources like wind and solar power have achieved a large-scale integration into most of the continent’s energy systems. At the same time, most European nations are continuously limiting the use of conventional sources for electric power generation, considering their negative impact on climate change. They adopt energy policies based on a low-carbon model of electricity production principally supported by renewables, in an attempt to mitigate the consequences to the environment and enhance energy security. In this thesis, we investigate the historical reforms in electricity components and the transformation of these systems across 30 European countries. A key outcome of this research is the formation of an energy identity for each nation, by examining the composition of the power generation mix and total generation capacity. We also study the evolution in the use of renewables for electricity generation and discuss how the changes in the use of each energy source affect capacity factors. Finally, the research provides useful conclusions about the effect of energy transition and the continents’ economic growth on electricity markets.

Abstract in Greek

Ο τομέας της ηλεκτρικής ενέργειας στην Ευρώπη έχει υποστεί σημαντικές αλλαγές τα τελευταία 30 χρόνια. Οι τεχνολογικές εξελίξεις των τελευταίων δεκαετιών στον κλάδο, έχουν εισαγάγει νέες και αποτελεσματικές μεθόδους παραγωγής ηλεκτρικής ενέργειας και ανανεώσιμες πηγές όπως η αιολική και η ηλιακή ενέργεια έχουν επιτύχει μια μεγάλης κλίμακας ενσωμάτωση στα περισσότερα ενεργειακά συστήματα της ηπείρου. Ταυτόχρονα, τα περισσότερα ευρωπαϊκά κράτη περιορίζουν συνεχώς τη χρήση συμβατικών πηγών για την παραγωγή ηλεκτρικής ενέργειας, λαμβάνοντας υπόψη τις αρνητικές επιπτώσεις τους στην κλιματική αλλαγή. Υιοθετούν ενεργειακές πολιτικές που βασίζονται σε ένα μοντέλο ηλεκτροπαραγωγής χαμηλών εκπομπών άνθρακα που υποστηρίζεται κυρίως από ανανεώσιμες πηγές, σε μια προσπάθεια να μετριάσουν τις συνέπειες στο περιβάλλον και να ενισχύσουν την ενεργειακή ασφάλεια. Σε αυτή τη διπλωματική διερευνούμε τις ιστορικές μεταβολές στις συνιστώσες της ηλεκτρικής ενέργειας καθώς και τον μετασχηματισμό των συστημάτων ηλεκτρικής ενέργειας σε 30 ευρωπαϊκές χώρες. Αποτέλεσμα της έρευνας είναι η διαμόρφωση μιας ενεργειακής ταυτότητας για κάθε κράτος, εξετάζοντας τη σύνθεση του μείγματος ηλεκτροπαραγωγής και την συνολική εγκατεστημένη ισχύ. Μελετάται επίσης η εξέλιξη στη χρήση ανανεώσιμων πηγών για την παραγωγή ηλεκτρικής ενέργειας και συζητείται πώς οι μεταβολές στη χρήση κάθε πηγής επηρεάζει τους συντελεστές δυναμικότητας. Τέλος, η έρευνα παρέχει χρήσιμα συμπεράσματα σχετικά με την επίδραση της ενεργειακής μετάβασης και της οικονομικής ανάπτυξης της ηπείρου στις αγορές ηλεκτρικής ενέργειας.

Extended abstract in Greek

Αντικείμενο της παρούσας εργασίας αποτελεί η μελέτη και αξιολόγηση των ιστορικών μεταβολών σε βασικές συνιστώσες της ηλεκτρικής ενέργειας στην Ευρώπη. Συγκεκριμένα, γίνεται μια εκτενής ανασκόπηση των αλλαγών στον τομέα λαμβάνοντας υπόψιν διάφορα χαρακτηριστικά, όπως η ηλεκτροπαραγωγή και η εγκατεστημένη ισχύς σε 30 Ευρωπαϊκές χώρες και καλύπτοντας μια χρονική περίοδο τριών δεκαετιών.

Η ηλεκτρική ενέργεια αποτελεί σήμερα βασικό αγαθό και αναπόσπαστο στοιχείο της καθημερινότητας του ανθρώπου, καθώς καλύπτει ένα μεγάλο εύρος των αναγκών και δραστηριοτήτων του. Οι εγκαταστάσεις παραγωγής ενέργειας χρησιμοποιούν ένα ευρύ φάσμα τεχνολογιών και πρωτογενών πηγών για ηλεκτροπαραγωγή. Οι πρωτογενείς πηγές ενέργειας μπορούν να διακριθούν σε τρείς βασικές κατηγορίες, τις συμβατικές πηγές, τα ανανεώσιμα και τα πυρηνικά.

Οι συμβατικές μορφές ενέργειας, αποτελούνται από ορυκτά καύσιμα όπως το πετρέλαιο, το φυσικό αέριο και οι γαιάνθρακες και για το μεγαλύτερο μέρος της ανθρώπινης ιστορίας χρησιμοποιούνταν ως η κύρια πηγή για την κάλυψη των ενεργειακών αναγκών. Θεωρούνται μη ανανεώσιμες πηγές καθώς βρίσκονται σε πεπερασμένες ποσότητες στη γη και ο ρυθμός ανανέωσης τους -της τάξης πολλών εκατομμυρίων ετών- δεν είναι συγκρίσιμος με την ανθρώπινη κλίμακα. Μέχρι σήμερα αποτελούν τον πιο ευρέως διαδεδομένο τρόπο παραγωγής ηλεκτρικής ενέργειας παγκοσμίως, μετατρέποντας τη θερμική ενέργεια από την καύση των ορυκτών καυσίμων σε ηλεκτρισμό.

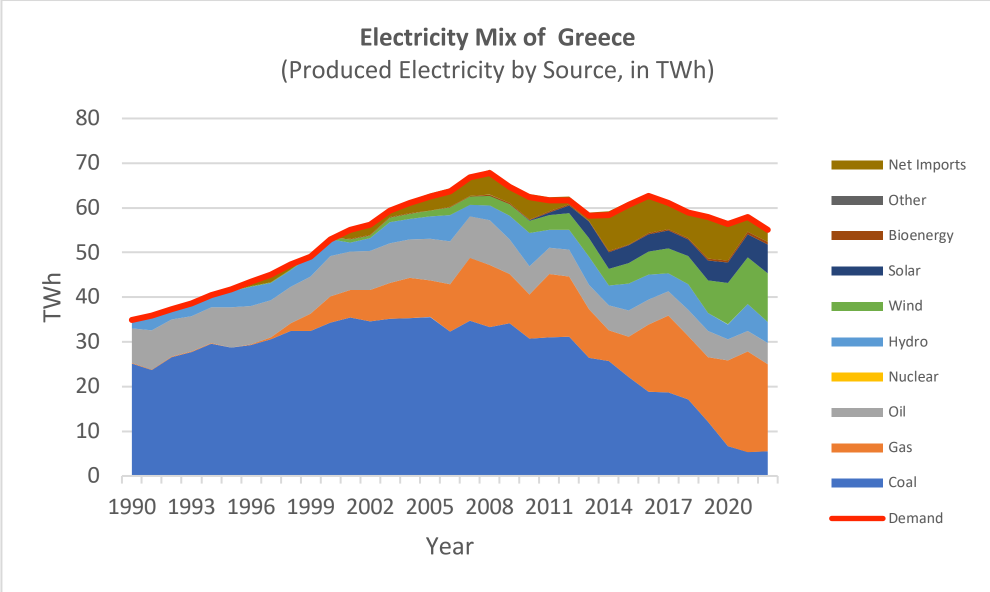
Αντίθετα, ανανεώσιμες χαρακτηρίζονται οι μορφές ενέργειας που προέρχονται από φυσικές διαδικασίες, και των οποίων βασικό χαρακτηριστικό είναι η διαχρονική ανανέωση και διαθεσιμότητα σε μικρές χρονικές κλίμακες με αποτέλεσμα να θεωρούνται πρακτικά ανεξάντλητες. Σε αυτές περιλαμβάνονται η ηλιακή, η αιολική και η υδροηλεκτρική ενέργεια, η γεωθερμία, η βιομάζα, η ενέργεια που προέρχεται από την παλίρροια και τους θαλάσσιους κυματισμούς κ.α. Χαρακτηριστικό των περισσότερων ανανεώσιμων είναι η μη ελεγχόμενη παραγωγή ενέργειας, καθώς σε αντίθεση με τις συμβατικές μορφές ενέργειας, η παραγωγή εξαρτάται από τις διακυμάνσεις στις φυσικές διεργασίες όπως η ύπαρξη ηλιοφάνειας ή η ταχύτητα του ανέμου. Εξαίρεση αποτελεί η γεωθερμία, η βιομάζα καθώς και τα μεγάλα υδροηλεκτρικά έργα με δυνατότητα αποθήκευσης του νερού.

Τέλος στα πυρηνικά, η παραγωγή ενέργειας γίνεται μέσω πυρηνικών αντιδράσεων στα άτομα ραδιενεργών χημικών στοιχείων όπως το ουράνιο, κατά τις οποίες εκλύονται σημαντικές ποσότητες θερμότητας που στη συνέχεια μετατρέπονται σε ηλεκτρισμό.

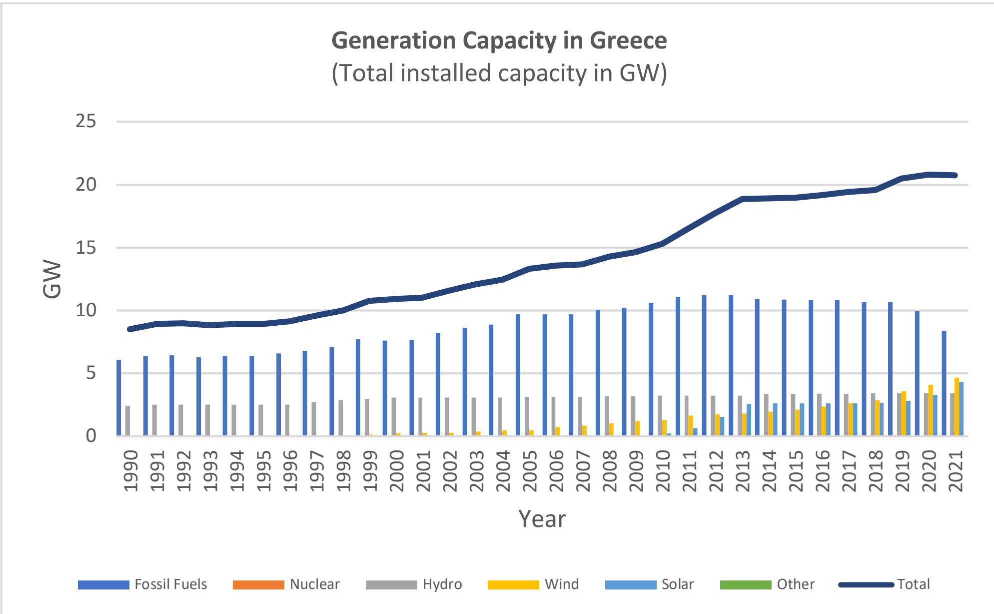
Η χρήση συμβατικών πηγών στην ηλεκτροπαραγωγή είναι πολύ εκτεταμένη σήμερα, καθώς είναι μια σχετικά φθηνή μέθοδος παραγωγής ηλεκτρικής ενέργειας, και το γεγονός ότι δεν εξαρτάται από καιρικές και κλιματικές συνθήκες την καθιστά εξαιρετικά αξιόπιστη. Για το λόγο αυτό, τα ορυκτά καύσιμα και ιδιαίτερα οι γαιάνθρακες, είναι αρκετά δημοφιλείς πηγές ηλεκτρικής ενέργειας και πολλές Ευρωπαϊκές χώρες εξαρτώνται σε μεγάλο βαθμό από αυτά για την κάλυψη των ενεργειακών τους αναγκών. Παρόλα αυτά η χρήση ορυκτών καυσίμων έχει αρνητικό αντίκτυπο στο περιβάλλον, αφού η καύση τους απελευθερώνει στην ατμόσφαιρα τεράστιες ποσότητες αερίων υπεύθυνων για το φαινόμενο του θερμοκηπίου όπως το διοξείδιο του άνθρακα και μια σειρά άλλων ατμοσφαιρικών ρύπων που έχουν αποδειχθεί επιβλαβείς για την υγεία. Στον αντίποδα, οι ανανεώσιμες πηγές -οι οποίες πολλές φορές χαρακτηρίζονται ως ήπιες- έχουν ελάχιστο έως μηδενικό αποτύπωμα άνθρακα και εκπομπών άλλων ρυπογόνων αερίων, καθιστώντας τες έτσι καθαρές μορφές ενέργειας.

Τα παραπάνω, σε συνδυασμό με τις ταχείες εξελίξεις και βελτιώσεις στην τεχνολογία των ανανεώσιμων, και ειδικά της ηλιακής και της αιολικής ενέργειας, έχουν οδηγήσει στο σταδιακό περιορισμό στη χρήση ορυκτών καυσίμων. Οι περισσότερες Ευρωπαϊκές χώρες αν δεν το έχουν ήδη πράξει, θεσπίζουν κανόνες και εφαρμόζουν νέες ενεργειακές πολιτικές μετατοπισμένες προς ένα μοντέλο ηλεκτροπαραγωγής που στηρίζεται στις ανανεώσιμες πηγές, αυξάνοντας μέρα με τη μέρα το ποσοστό ενσωμάτωσης τους στο ενεργειακό μείγμα σε μια προσπάθεια να μετριάσουν τις επιπτώσεις της χρήσης των συμβατικών πηγών ενέργειας στην κλιματική αλλαγή.

Στην παρούσα διπλωματική, διερευνώνται οι παραπάνω μεταβολές καθώς και η επιρροή τους σε διάφορες συνιστώσες της ηλεκτρικής ενέργειας όπως το ενεργειακό μείγμα, η ζήτηση ή η εγκατεστημένη ισχύς. Αρχικά, δημιουργείται ένα ενεργειακό προφίλ για κάθε μία από τις υπό μελέτη χώρες (ΕΕ-27, Νορβηγία, Ισλανδία, Ηνωμένο Βασίλειο), στο οποίο αποτυπώνεται η εξέλιξη του ενεργειακού της κλάδου μέσω των αλλαγών στο μείγμα ηλεκτροπαραγωγής. Η **Εικόνα 1**, παρουσιάζει τις αλλαγές όσον αφορά τη χρήση της εκάστοτε πηγής ενέργειας στην Ελλάδα, οι οποίες είναι ενδεικτικές των αντίστοιχων μεταβολών στις περισσότερες χώρες της Ευρώπης. Είναι εμφανής δηλαδή, η μεγάλη μείωση στη χρήση ορυκτών καυσίμων· συγκεκριμένα για τη χώρα μας πρακτικά η κατάργηση του πολύ ρυπογόνου λιγνίτη και η μερική αντικατάσταση του από το φυσικό αέριο. Ταυτόχρονα, διακρίνεται η ραγδαία αύξηση στη συμμετοχή των ανανεώσιμων, και κυρίως της αιολικής και ηλιακής ενέργειας στην παραγωγή ιδίως μετά το 2000 και το 2010 αντίστοιχα, αλλά και στην συνολική εγκατεστημένη ισχύ της χώρας (**Εικόνα 2**). Αξίζει να αναφερθεί πώς το ίδιο περίπου μοτίβο αντικατάστασης των συμβατικών μορφών από ανανεώσιμες εντοπίζεται στο μεγαλύτερο μέρος των Ευρωπαϊκών κρατών που μελετάμε.

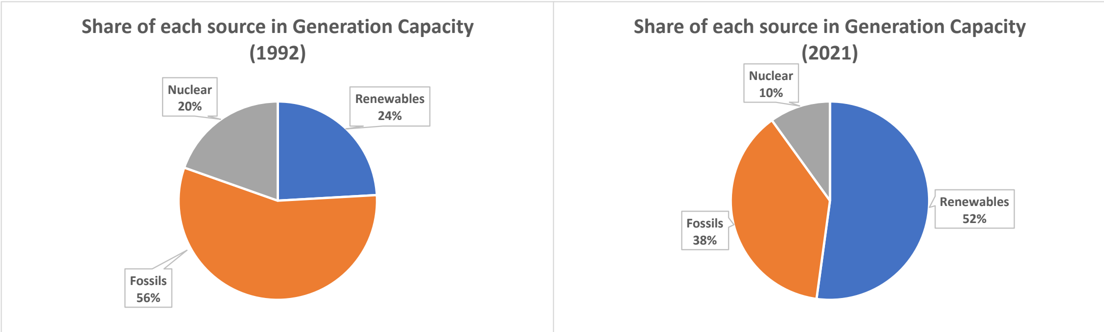


Εικόνα 1: Παραγόμενη ηλεκτρική ενέργεια στην Ελλάδα ανά πηγή από το 1990. Η κόκκινη γραμμή υποδεικνύει τη ζήτηση.



Εικόνα 2: Εγκατεστημένη ισχύς στην Ελλάδα από το 1990.

Στη συνέχεια, μελετάται αυτοτελώς η περίπτωση των ανανεώσιμων πηγών και γίνονται οι απαραίτητες συγκρίσεις με σκοπό την αποτύπωση των μεταβολών σε όρους εγκατεστημένης ισχύος και παραγωγής ηλεκτρικής ενέργειας σε μία χρονική περίοδο 30 ετών. Η διερεύνηση γίνεται τόσο υπό το πρίσμα κάθε πηγής χωριστά -επικεντρώνοντας την μελέτη στα υδροηλεκτρικά, την ηλιακή και την αιολική ενέργεια- όσο και σε επίπεδο ανανεώσιμων συνολικά. Όπως διακρίνουμε στην **Εικόνα 3**, το 2021 οι εγκαταστάσεις που βασίζονται σε ανανεώσιμες πηγές αποτελούσαν πάνω από τη μισή συνολική εγκατεστημένη ισχύ στις υπό μελέτη Ευρωπαϊκές χώρες, σε αντίθεση με το 1992 οπού κάλυπταν μόλις το ένα τέταρτο αυτής, αντικαθιστώντας σε σημαντικό βαθμό τόσο τα ορυκτά καύσιμα όσο και τα πυρηνικά, των οποίων η συνολική ισχύς μειώθηκε αθροιστικά από το 76% σε λιγότερο από 50% μέσα σε μία περίοδο τριών δεκαετιών. Η κυριαρχική τάση των ανανεώσιμων στον τομέα είναι το ίδιο εμφανής και σε όρους ηλεκτροπαραγωγής, καθώς από τις αρχές της δεκαετίας του 2020 και έπειτα, το μεγαλύτερο ποσοστό της παραγόμενης ηλεκτρικής ενέργειας προέρχεται αποκλειστικά από ανανεώσιμες πηγές.

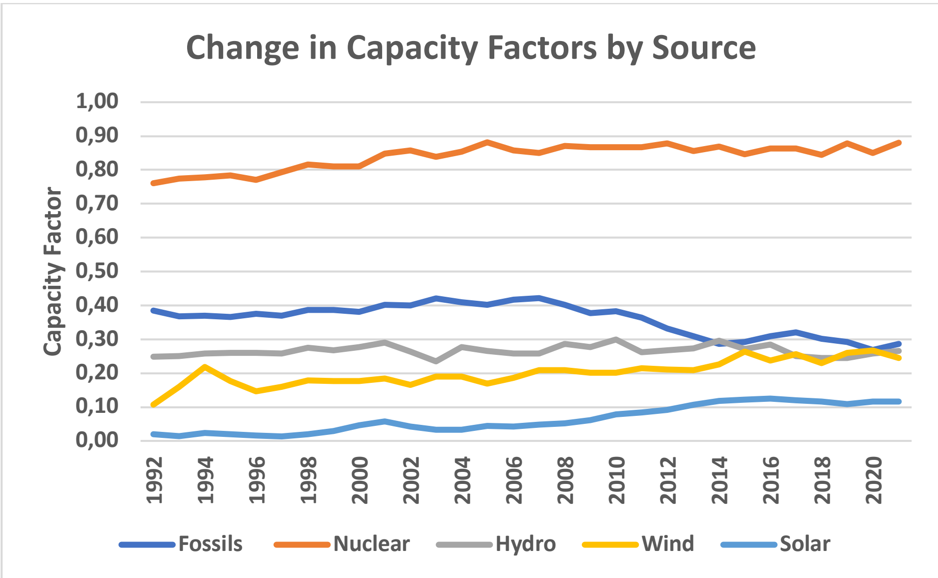


Εικόνα 3: Συνολική εγκατεστημένη ισχύς ανά πηγή ενέργειας σε 30 Ευρωπαϊκές χώρες το 1992 και το 2021.

Αξίζει να σημειωθεί ότι η ραγδαία αύξηση στη χρήση των ανανεώσιμων πηγών για την παραγωγή ενέργειας, γίνεται ορατή για πρώτη φορά μετά τα μέσα του 2000 και οφείλεται λιγότερο στα υδροηλεκτρικά -των οποίων η ισχύς και παραγωγή παρέμειναν πρακτικά αμετάβλητες- και περισσότερο στην εκθετική ανάπτυξη της ηλιακής και της αιολικής ενέργειας και την ταχεία ενσωμάτωση τους στα ηλεκτρικά δίκτυα της κάθε χώρας.

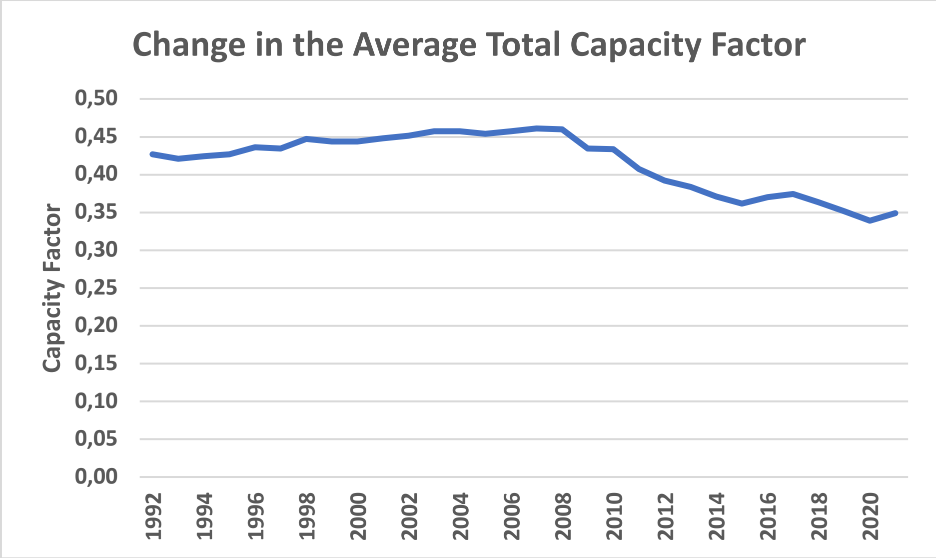
Ταυτόχρονα, μελετώνται οι μεταβολές στους συντελεστές δυναμικότητας, δηλαδή στο λόγο μεταξύ της παραγόμενης ηλεκτρικής ενέργειας προς τη θεωρητικά μέγιστη που θα μπορούσε να παραχθεί με βάση την εγκατεστημένη ισχύ σε ένα συγκεκριμένο χρονικό διάστημα (συνήθως αναφέρεται σε ετήσια κλίμακα). Η διερεύνηση γίνεται πάλι τόσο σε επίπεδο πρωτογενών πηγών ενέργειας όσο και συνολικά. Ο συντελεστής δυναμικότητας είναι ένας χρήσιμος δείκτης που μπορεί να μετρήσει την απόδοση και την αποτελεσματικότητα, και κατά κάποιο τρόπο αποτελεί την ταυτότητα ενός ενεργειακού έργου ή πηγής ενέργειας συνολικά. Μπορεί να επηρεαστεί από διάφορους παράγοντες όπως το είδος του σταθμού ηλεκτροπαραγωγής ή η πρωτογενής πηγή ενέργειας. Άλλοι παράγοντες που επηρεάζουν τον συντελεστή δυναμικότητας είναι οι διακοπές λειτουργίας των σταθμών παραγωγής (προγραμματισμένες με σκοπό τη συντήρηση και τον ανεφοδιασμό, απρόσμενες βλάβες κλπ.) και κυρίως επιχειρησιακές αποφάσεις που αφορούν τη λειτουργία και συνδέονται σε μεγάλο βαθμό με την ενεργειακή πολιτική που ακολουθεί κάθε χώρα απέναντι στη χρήση κάθε μορφής ενέργειας.

Οι ανανεώσιμες πηγές, και ιδιαίτερα οι μη ελεγχόμενης παραγωγής όπως η αιολική και η ηλιακή ενέργεια, τείνουν να έχουν σημαντικά χαμηλότερους συντελεστές δυναμικότητας, κυρίως λόγω της μεταβαλλόμενης φύσης και διαθεσιμότητας τους. Αντίθετα, στα ορυκτά καύσιμα και στην πυρηνική ενέργεια οι συντελεστές δυναμικότητας παρουσιάζουν αισθητά μεγαλύτερες τιμές. Συγκεκριμένα, στους πυρηνικούς αντιδραστήρες, οι τιμές είναι αρκετά μεγάλες καθώς η λειτουργία είναι σχεδόν συνεχής και σε μέγιστη ισχύ. Οι θερμικές μονάδες παραγωγής που λειτουργούν με ορυκτά καύσιμα έχουν επίσης μεγάλους συντελεστές, ωστόσο μικρότερους από τα πυρηνικά καθώς μπορεί να λειτουργούν είτε με μειωμένη ισχύ (για έργα βάσης) είτε για μικρότερο χρονικό διάστημα (για έργα αιχμής). Στην **Εικόνα 4**, διακρίνονται οι μέσοι συντελεστές δυναμικότητας ανά πηγή ενέργειας στις υπό μελέτη χώρες μεταξύ 1992 και 2021. Μπορούμε να συμπεράνουμε ότι η μείωση των τιμών των συντελεστών δυναμικότητας στα ορυκτά καύσιμα οφείλεται στην σημαντική μείωση της παραγωγής ηλεκτρικής ενέργειας από μη ανανεώσιμες πηγές, ενώ ταυτόχρονα, η αύξηση των τιμών στα ηλιακά και στα αιολικά βασίζεται στην ανάπτυξη νέων τεχνολογιών που αυξάνουν την απόδοση των συγκεκριμένων συστημάτων.



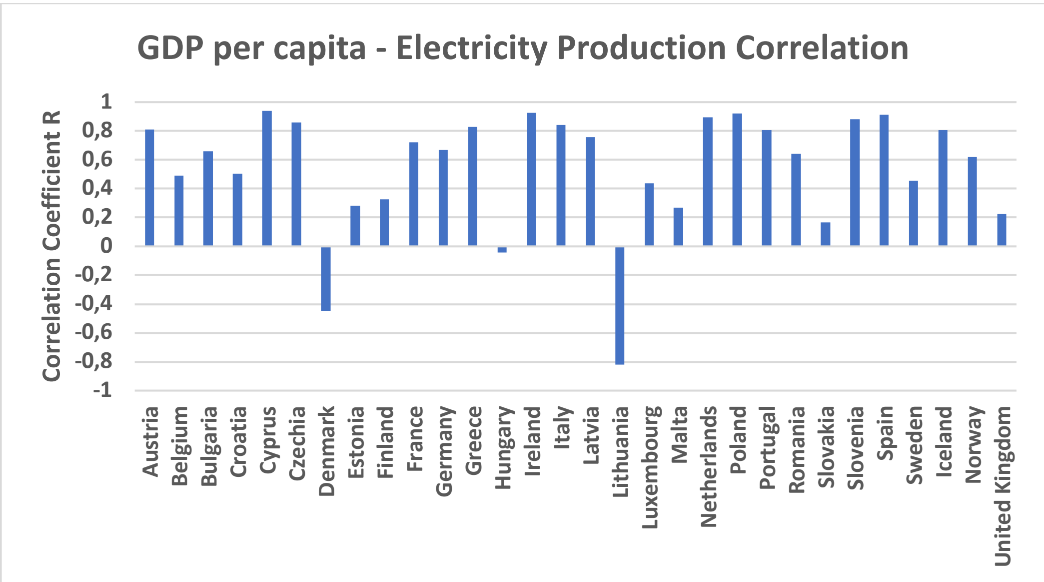
Εικόνα 4: Μέσοι συντελεστές δυναμικότητας ανά πηγή ενέργειας σε 30 Ευρωπαϊκές χώρες μεταξύ 1992 και 2021.

Αθροιστικά, ο συνολικός συντελεστής δυναμικότητας έχει παρουσιάσει μία σημαντική μείωση στις περισσότερες Ευρωπαϊκές χώρες και όπως φαίνεται στην **Εικόνα 5**, ο μέσος συντελεστής δυναμικότητας έχει μετακινηθεί από τιμές κοντά στο 0,45 το 1990, σε τιμές μικρότερες του 0,35 στις αρχές της δεκαετίας του 2020. Η μείωση οφείλεται κυρίως -και γίνεται εμφανής μετά το πρώτο μισό της δεκαετίας του 2000- στην ραγδαία αύξηση της συνολικής εγκατεστημένης ισχύος της ηπείρου, (μέσω της ενσωμάτωσης των αιολικών και ηλιακών) ενώ η παραγωγή ηλεκτρικής ενέργειας παρέμεινε σχετικά σταθερή.



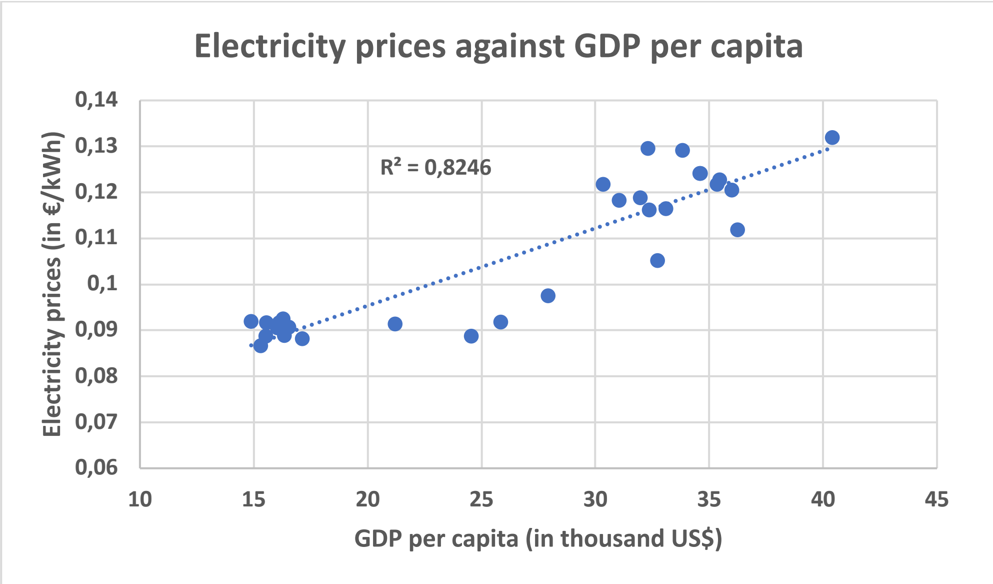
Εικόνα 5: Μέσος συνολικός συντελεστής δυναμικότητας σε 30 Ευρωπαϊκές χώρες μεταξύ 1992 και 2021.

Στο τέλος της παρούσας εργασίας, γίνεται μία σύντομη ανασκόπηση των οικονομικών της ηλεκτρικής ενέργειας στην Ευρώπη, εξετάζοντας τον αντίκτυπο βασικών οικονομικών δεικτών όπως το Ακαθάριστο Εγχώριο Προϊόν σε διάφορες συνιστώσες της ηλεκτρικής ενέργειας και διερευνώντας την επίδραση της οικονομικής ανάπτυξης της Ευρώπης στις τιμές της ηλεκτρικής ενέργειας. Συγκεκριμένα, εξάγονται συμπεράσματα όπως η άμεση σχέση μεταξύ του κατά κεφαλήν ΑΕΠ και της παραγωγής ηλεκτρικής ενέργειας στις περισσότερες υπό μελέτη χώρες -με ελάχιστες εξαιρέσεις- όπως βλέπουμε στην **Εικόνα 6**.



Εικόνα 6: Συσχέτιση μεταξύ κατά κεφαλήν ΑΕΠ και ηλεκτροπαραγωγής σε επιλεγμένες Ευρωπαϊκές χώρες.

Ταυτόχρονα, η μεταβολή του κατά κεφαλήν ΑΕΠ φαίνεται να επηρεάζει και τις τιμές της ηλεκτρικής ενέργειας στην Ευρώπη καθώς όπως φαίνεται στην **Εικόνα 7**, υπάρχει πολύ ισχυρή θετική συσχέτιση μεταξύ των δύο. Εξάγουμε επομένως το κατά τα αλλά αναμενόμενο συμπέρασμα, ότι οι τιμές της ηλεκτρικής ενέργειας συνδέονται άμεσα με την οικονομική ανάπτυξη στην Ευρώπη. Η αύξηση του κατά κεφαλήν ΑΕΠ οδηγεί σε αύξηση της ζήτησης ηλεκτρικής ενέργειας λόγω της υψηλότερης βιομηχανικής δραστηριότητας και του βελτιωμένου βιοτικού επιπέδου, γεγονός που οδηγεί τελικά σε άνοδο των τιμών της ηλεκτρικής ενέργειας.



Εικόνα 7: Συσχέτιση μεταξύ κατά κεφαλήν ΑΕΠ και τιμών ηλεκτρικής ενέργειας.

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Chapter 1: Introduction

1.1 Research objectives

The electricity domain in Europe has undergone significant reforms during the last 30 years. For the largest part of the European history, combustible fuels were a key determinant in the power generation and supply industry, and their use was and remains extensive because it is a cheap and effective way of producing electricity. However, the usage of fossil fuels has a negative impact on the environment. The burning of combustibles, releases into the atmosphere huge amounts of gases responsible for the greenhouse effect, like carbon dioxide (CO_2) and a variety of other air pollutants, thereby contributing to climate change. Hence, European countries have taken measures and have modified their energy strategies, by seeking cleaner substitutes for fossil fuels in an effort to mitigate the consequences of climate change to the environment.

For a long time, hydropower and nuclear power were the only low-carbon sources of electricity present in the electricity grid. However, the technological advancements of the last decades in the sector have introduced new and effective methods of electricity production, and renewable sources (e.g. wind and solar) have achieved a large-scale integration into the continent's energy system. This, along with the favourable policies, regarding carbon-neutrality, followed by most nations has led to an explosive growth of renewables and triggered a series of changes in electricity components across Europe.

This thesis investigates the evolution of the electricity domain in Europe during a period spanning from the early 1990s, when the only widely used renewable source was hydropower, to the early 2020s, observing the rise and fall of variables and combustibles respectively.

The main objectives of this research are outlined as follows:

1. Provide a comprehensive overview of the primary sources used for electricity generation,
2. Outline the changes in the composition of the electricity mix of each European country,
3. Investigate the incorporation of renewable energy into the energy systems,
4. Discuss the effects of the changes in energy policies on capacity factors,
5. Outline the impact of energy transition and economic growth on electricity markets.

1.2 Thesis structure

This thesis is divided into seven chapters.

The **first chapter** introduces the subject and the research objectives of the thesis.

The **second chapter** provides a literature overview of the history of electric power including basic methods and primary sources used for electricity generation, along with a description of the electricity markets in Europe.

In the **third chapter**, we create an energy identity for a large number of European countries by providing information about the historical reforms in the composition and the evolution of each country's electricity mix and total generation capacity.

The **fourth chapter** is dedicated exclusively to the changes in the use of renewable energy sources for electricity generation.

The **fifth chapter** investigates the changes in the capacity factors of each separate electricity source and in the total capacity factors for many European countries.

The **sixth chapter** includes a brief review of how basic economic indicators like GDP affect electricity components and how Europe's economic growth influences electricity prices.

The **seventh chapter** summarizes the conclusions and the future perspective of the research.

Chapter 2: Literature overview

2.1 About electric power

Power P is the amount of energy E that is transferred divided by the unit of time t. In the SI (International System of Units) the unit is the Watt (W) that equals to one Joule (J) per second (s). Analyzing further the Joule to the SI base units, the Watt equals to:

$$1\,W = 1\,\frac{J}{s} = 1\,\frac{N \cdot m}{s} = 1\,\frac{kg \cdot m^2}{s^3}$$

Therefore, Electric Power can be defined as the rate at which the energy is transferred throughout an electrical circuit. It is produced by an electric current I passing through an electric potential V measured in Amperes (A) and Volts (V) respectively:

$$P = \frac{E}{t} = V \cdot I$$

The flow of the charged particles through an electrical conductor, known as the electric current, can be distinguished in two different types, the direct current (DC) and the alternating current (AC). Direct current (DC) occurs when the flow of energy has a constant direction, and the voltage has the same value over time. On the other hand, in alternating current (AC), the direction of the flow changes periodically from positive to negative, and the voltage is constantly switched accordingly. Direct current is usually used in batteries, electronic devices and specific industrial applications, while alternating current is the main method of delivering electricity via transmission lines to domestic and business consumers (Article, MPS, n.d.).

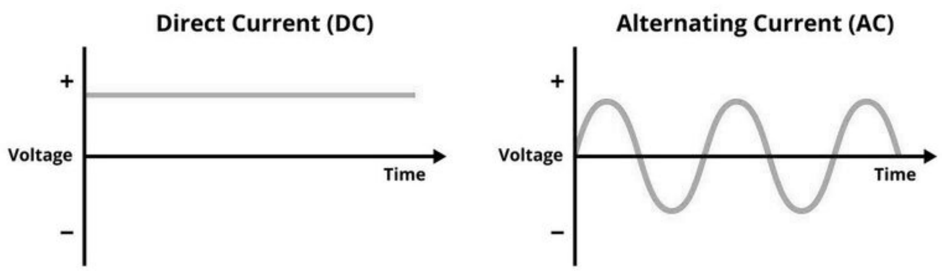

Figure 2.1: Voltage change over time in direct (DC) and alternating current (AC).

As a form of energy, electric power is usually generated by the convention of other types of energy into electrical, using devices known as electric generators, while the production of electricity takes place in facilities known as power stations -or most commonly- power plants (The Editors of Encyclopaedia Britannica, 2024).

2.2 Methods of electricity generation

The majority of the worldwide generated electricity comes from generators that are based on the 1820s and 1830s discoveries of the British scientist Michael Faraday. According to Faraday's experiments, electric current was created through a loop of a conductor - usually a copper wire - known as a "Faraday disk", by the rotation of the loop around the two opposite poles of a magnet (U.S. EIA, n.d.). This prototype method, which utilized the properties of magnetism to produce electricity by transforming the mechanic (kinetic) energy of the disk, led gradually to the design of the modern electromagnetic generators used today for most of electricity production.

Currently, apart from electromagnetic generators, other ways of electricity generation include photovoltaic systems that use the photovoltaic effect to transform the sunlight into electric power, electrochemical applications which produce electricity via chemical energy etc.

2.2.1 Turbine based generators

As already mentioned, most of the power generation facilities today are using electromagnetic generators to produce electricity. The architecture of these generators has arisen from the early Faraday disks; they consist of a large rotating electromagnetic shaft in the middle -named a rotor- which is surrounded by a series of separated wire foils that form a large, fixed cylinder, the so-called stator. The rotation of the shaft creates an electric current in each one of the cylinder's foils, which are then combined and form a larger current (U.S. EIA, n.d.). The produced electricity then is ready to enter the grid, and to head to the consumers.

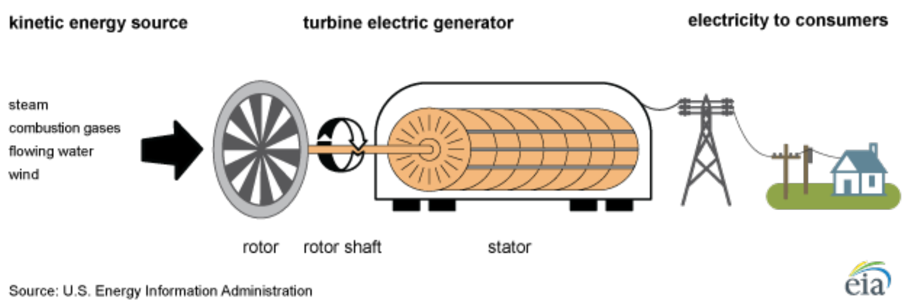

Figure 2.2: Electricity generation sequence from an electric turbine.

These electromagnetic generators are designed to utilize the kinetic energy of the rotor and transform it into electric power, so they need to be driven by a turbine. The turbine based generators use a moving fluid -most commonly steam, water, or air- to push a series of blades that are attached to the electromagnetic shaft. The force that acts on the blades leads to the rotation of the rotor, thus gaining kinetic energy which is then transformed into electricity. The most common types of turbines are steam, hydroelectric and wind turbines which use the steam flow, water and airflow to operate, respectively.

Steam turbines are the most used type of turbine, and they generate the largest percentage of electric power of any other type of turbine. The power plants that use this type of turbines are equipped with boilers where fuel is burned to heat up the water and produce steam (U.S. EIA, n.d.). Then the steam is used to feed the turbine that moves the generator. The fuel that is been used in these facilities ranges from combustible fuels like coal, oil, or natural gas, to nuclear fuel in the nuclear reactors. Many geothermal power plants also use steam turbines.

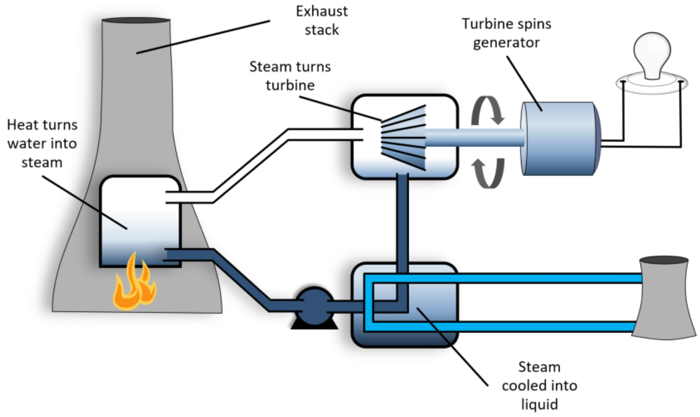

Figure 2.3: Steam turbine operation diagram

Hydroelectric turbines use the force created by the motion of the water to rotate the blades and spin the electromagnetic generator. They frequently utilize stored water, found in reservoirs, and taking advantage of a height difference they convert the mechanical energy of the water to electricity. In other types of hydroelectric plants, the turbines run directly on the river and with little to no storage capability, they generate electricity based on the water flow at the specific moment (U.S. EIA, n.d.).

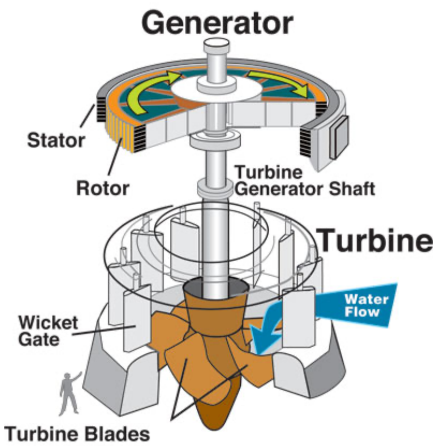

Figure 2.4: Water operating turbine

In wind turbines, the power to rotate the blades that drive the generator is found in the airflow of the wind. The wind turbines are distinguished into two different categories based on the direction of the axis of the rotor (U.S. EIA, n.d.). These are the vertical-axis and the horizontal-axis turbines, with the last ones being the most frequently used.

2.2.2 Photovoltaic effect

The photovoltaic effect is a phenomenon that occurs in the photovoltaic cells, thanks to which it is possible to produce electricity by sunlight. It was discovered by Edmond Becquerel in 1839; while he was doing experiments in solar cells, he found out that an electric potential was created when the cell plates were exposed to sunlight (Photovoltaic Effect - Energy Education, n.d.).

The effect takes place inside the photovoltaic cells. The cells are metal sheets comprised of two layers of semi-conductor materials. The two distinct layers (one of them is p-type and the other n-type) are joined together and create a junction. The p-type layer is positively charged while the n-type is negative. After unified, an electric field is created between the two layers and the negatively charged electrons move to the positive p-type layer.

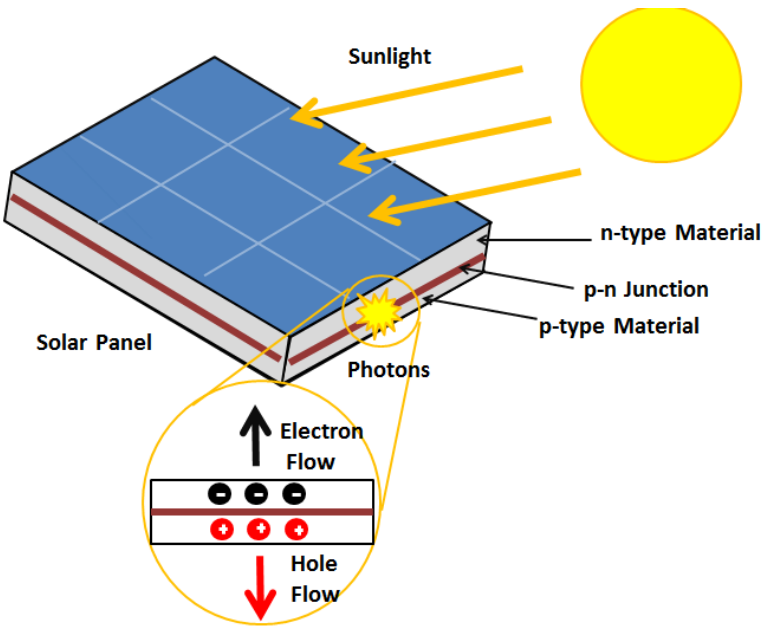

Figure 2.5: A diagram showing the photovoltaic effect.

Sunlight is composed of photons, a form of solar radiation, which are practically solar energy. When the sunlight hits a solar cell, some of the photons pass through the cell, some are reflected by the surface and only a small portion is absorbed by the semi-conducting materials. These photons, when in proper quantity, transfer energy to the electrons which then tend to move through the junction towards the n-type material, and an electric potential is formed between the two layers. If connected to an electrical circuit, the solar cells transform the energy of the sunlight into electric power (Energy Education, n.d.).

Practically, solar cells convert solar energy to electricity. This method is widely used today, and solar power plants are one of the fastest growing ways of producing electricity nowadays.

2.3 Sources of electricity

The power production facilities, use a wide range of energy sources and technologies to generate electricity. These can be distinguished into three main categories; conventional energy which comes from fossil fuels, nuclear energy and renewable energy which combines a variety of sources like hydropower, solar, wind, and others.

2.3.1 Conventional sources

Conventional sources of energy, also known as non-renewable sources, are the oldest utilized source of energy in the history of humankind. They mainly consist of fossil fuels (e.g. natural gas, oil, coal) which are, in general, found in finite quantities on earth. They are considered as non-renewables because the pace of their regeneration is not sufficient compared to the timescale of human life. They are widely used by power production facilities as burning materials, as they use thermal power to generate electricity. Today they are the most widely used way of electricity production worldwide.

The fossil fuels that are mainly used are coal, oil, and natural gas. Coal is a dark grey to black colored sedimentary rock that is found deep under the surface of the earth. It was created billions of years ago, during a process in which dead plant remains buried underground were gradually transformed into peat and eventually coal, assisted by the presence of high temperature and high-pressure conditions. Oil, also known as petroleum, is a dark colored liquid and it is also found in the underground, trapped between layers of the earth’s crust. It was formed during a process similar to the previous one when dead organic matter was buried under layers of rock. Lastly, natural gas is a source of energy found in the gas state right above the petroleum reserves and it is primarily composed of methane. All the above, are flammable materials which are extracted from the earth using mining or pumping methods and are used by the power plants as burning fuel to produce electricity.

The use of combustible fuels in the power generation and supply industry is very extensive today because it is a relatively cheap method of producing electricity. Fossil fuels -in most cases- are easy to find and extract from the ground, transport, and use. In addition, they do not depend on the climate conditions or the weather of a region at a specific time, thus making them a reliable source of energy. In this vein, fossil fuels and especially coal, are the dominant source of electricity today and many countries highly depend on them for their energy supply.

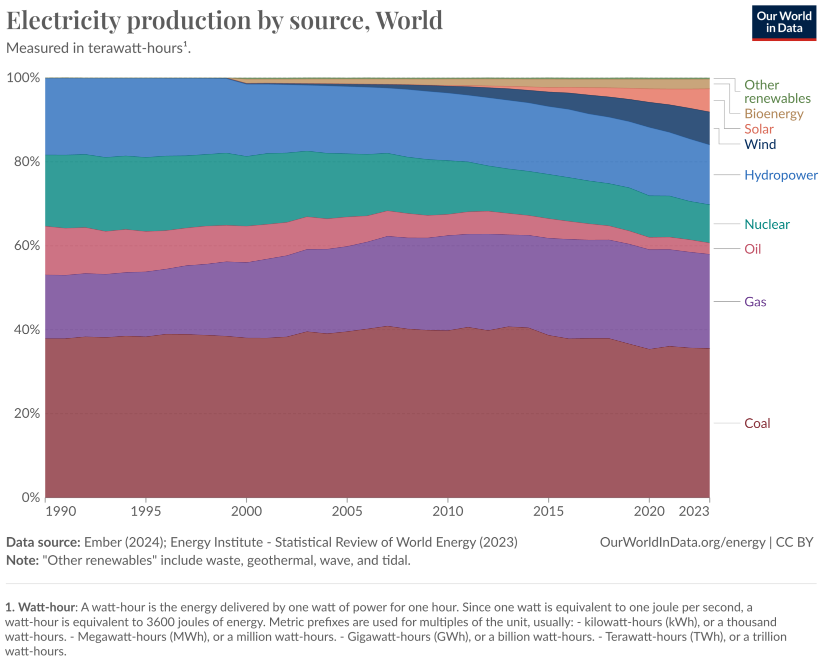

Figure 2.6: Global electricity production by source from 1990.

Despite being a cheap and effective source of electricity, the usage of fossil fuels has a negative impact on the environment contributing at an ascending rate to changing climate. The burning of combustibles, releases into the atmosphere huge amounts of gases responsible for the greenhouse effect like carbon dioxide (CO_2) and a variety of other air pollutants like particles of ash that have been proven harmful to our health. Considering that today at least 60 percent of the total electricity production in the world comes from fossil fuels (Generating Electricity: Fossil Fuels, 2020), the problem's extent is large. Therefore, the need to shift to more clean forms of energy is clear.

2.3.2 Nuclear power

Nuclear power is a way of obtaining electricity by the energy that is released during a nuclear reaction. The most common way to achieve it is by nuclear fission, a type of nuclear reaction, during which the atoms of radioactive chemical elements like Uranium, split into two or more smaller parts and emit a significant amount of energy (IAEA, n.d.). The nuclear fission takes place inside the nuclear reactors of the power plants. These reactors use the heat energy that is been released by the fission happening in the atoms of a radioactive material (which is used as fuel) to produce steam. Then the steam turbines that were described earlier in the chapter, drive the electromagnetic generators, and produce electricity.

For a long time, nuclear power has been at the forefront of low-carbon electricity generation, as nuclear fission emits almost no carbon dioxide. For many countries, it is one of the largest sources of electricity. For instance, in France almost 75 percent of the total electricity comes from the operation of nuclear power plants. Another advantage of this specific source is the ability to produce a large amount of energy using a small amount of nuclear fuel. On the other hand, the disadvantages of nuclear power include difficulty in nuclear waste management (which require secure and long-term disposal) and the potential risk of an accident during the operation of the power plant. Although rare, the consequences of such an accident have been proven lethal for both human life and the environment.

Despite its handicaps, nuclear power plays an important role in many countries' energy mix as 10 to 15 percent of the global electricity production every year comes from nuclear power (Nuclear - IEA, n.d.). The advancing technology reduces the potential risks and nuclear power itself reinforces the efforts to limit the total carbon emissions by using a more sustainable fuel.

2.3.3 Renewable energy sources

Renewable energy sources can be defined as sources of energy that are found in nature and regenerate at a sufficient pace in comparison to the human timescale so they can be recreated long before they are consumed. The electricity produced by renewable sources can come from sun, wind, water, biomass, etc., and can be characterized as a more sustainable type of energy, as little to zero greenhouse gases are emitted during its production. Depending on how fluctuate they are, these sources can be distinguished into two separate categories:

- Variable Energy Sources: their availability strongly depends on time or weather conditions like solar power and wind power respectively,
- Controllable Energy Sources: their availability depends on their storage management (e.g. hydropower in reservoirs) or simply on their consistency (e.g. geothermal energy).

As already described, solar power is produced by converting the sunlight radiation into electricity thanks to the photovoltaic effect. Solar power installations include photovoltaics (PV) consisting of solar cells and the necessary devices for the electricity output. These facilities produce energy based on the availability of direct sunlight (measured in kW/m^2) and the angle of incidence to the panels and are one of the fastest growing methods of generating electricity worldwide. The relatively new technology has increased up to ten times during the past decade its contribution to world electricity production and is currently responsible for at least 5 percent of the total electricity.

The power of the wind has continuously been used by humans for at least five thousand years in sectors like transport and agriculture. However, it was only until the 20^{th} century when it was first applied to methods of generating electricity. Today the wind is massively producing electric power using modern wind turbines. The power production coming from the wind depends on factors like the air density ρ, the area covered by the wind turbine A, and of course the wind speed V. The theoretical power of a wind turbine is given by the following equation:

$$P = \frac{1}{2} \cdot \rho \cdot A \cdot V^3$$

Wind is considered a variable energy source as the air speed at the time plays a specific role in the performance of the turbines; if the speed is lower or higher than necessary, there is dramatically lower or no production at all. Nevertheless, new technologies have flourished, and wind power is becoming more efficient and more popular every day. The electricity from wind is almost 10 percent of the global production with an ascending rate.

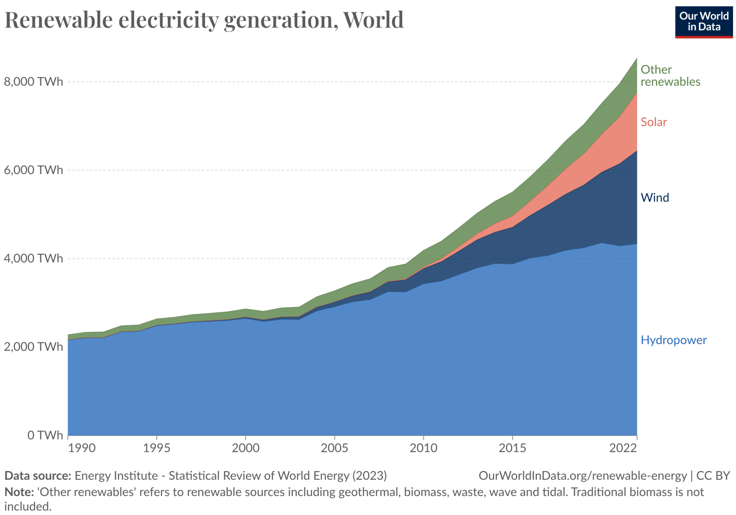

Figure 2.7: Global electricity production by renewable source since 1990.

Exactly like wind, humans understood early that they could take advantage of the power of water. From early antiquity, they created windmills on the river, using the kinetic energy of the flowing water to grind cereals and perform other tasks. Until the 19th century, they had already applied their previous knowledge to the field of energy production. Today, hydropower is produced both by high scale projects that include water storage like dams, and smaller -run off the river- facilities with little to no storage ability. At the same time, hydroelectric projects serve as the only large-scale energy storage systems based on today's technology. Finally, hydropower contributes to the low-carbon electricity production as it is the most used non-conventional source of electricity in the world, generating each year almost 15 percent of the world's electricity.

Apart from the above, there are also other forms of renewable energy like biomass, geothermic energy, and some experimental applications based on tide and wave power production, but their use is still limited. There are many advantages to the use of renewable sources for electricity production. Their low greenhouse gas emissions contribute to the mitigation of the consequences of climate change to the environment, and their abundance allows the continuous energy supply. For those reasons, renewable energy is becoming more competitive compared to the traditional ways of electricity production and it is adapted day after day more effectively into the energy mix of many countries.

2.4 Basic electricity components

2.4.1 Generation capacity

The installed generation capacity specifies the maximum amount of electricity production of each power installation. Under normal conditions, the value of the electricity capacity of a power plant is comparatively larger than the actual produced electricity (Anon n.d.). Most of those installations (both conventional and renewable) do not always operate at their full potential, principally because power production highly depends on the actual and on-time demand of the network for electricity. Additionally, in the case of renewable energy plants, the production is linked to the availability. For instance, capable wind and sunny weather conditions determine the amount of electricity produced by solar and wind power plants respectively. For all those reasons plus counting maintenance needs, much of the generation capacity goes unused.

At a national level installed capacity refers to the sum of the production plants of a specific country and it tends to be considerably greater than its maximum consumption in order to ensure the sufficiency of electricity supply even during the systems' demand peaks. Moreover, there is a national effort to integrate the networks, by connecting them neighboring countries' grids in order to reinforce the system and export the electricity surplus during low-demand hours.

2.4.2 Power generation mix

The power generation mix, also known as the electricity mix, is the combination of all the primary energy sources that are used to generate electric power in a specific region or country. The electricity mix should not be confused with the energy mix, as the latter refers to all the energy uses like transportation and heating, while the electricity mix includes solely electricity generation. The power generation mix plays a leading role in each country's energy security and economy in general. Diverse electricity mixes offer stability in the power supply, as they reduce the risks of depending on a single energy source. At the same time, as fossil fuels have been proven responsible for climate change, many countries work to increase the proportion of renewable energy sources in their mix, in an effort to reduce greenhouse gas emissions and mitigate environmental concerns.

2.4.3 The capacity factor

Capacity factor (cf) can be defined as the ratio of the generated electricity of a power facility (or a system of facilities), to the maximum electricity that could theoretically be produced in a specific period of time. In simple words, it is the total electrical output divided by the maximum possible output of the source if it always operated at full capacity (Scheig, 2023). Considering E the electricity produced, P_{max} the maximum capacity, and T the time, the capacity factor is expressed as:

$$cf = \frac{Actual\ Output}{Max. Possible\ Output} = \frac{E}{P_{max} \cdot T} = \frac{\int_0^T P(t)\,dt}{P_{max} \cdot T}$$

Typically, the capacity factor is measured on an annual time scale dividing the total electricity generation (in TWh) by the facility's installed capacity (usually in GW) multiplied by the 8760 hours of the year. For example, if a power plant has a generation capacity of 1 GW and produces 7 TWh of electricity over a period of one year, the capacity factor is estimated as:

$$cf = \frac{7\ TWh \cdot 1000 \frac{GW}{TW}}{1\ GW \cdot 8760\ h} = 0.80$$

2.5 Economic perspective of electricity – Electricity markets

Electricity is an essential good in modern society and it is a basic element of human activities both at a domestic and at an industrial level (EPEX SPOT, n.d.). It covers a vast range of needs and is vital for the existence and the development of society.

For the largest part of European history, the management of electricity generation and distribution was the responsibility of each country's power companies which were owned by the state and controlled the whole process until the final consumer. In the early 1990s European Union decided to create an Internal European energy market by separating the stages of the electricity supply chain, privatizing many of the until then state-owned power companies and creating competition, in an effort to make easier the interconnection and trade between the countries national grids and enhance energy security. The creation of the single electricity market has helped the achievement of the mentioned goals; it has furthermore contributed to the limitation of the monopoly in power supply and has allowed the existence of more market-driven prices (Guckian, 2023). Today the electricity market is regulated by a series of rules in order to control its operation, promote competition and reinforce the energy security and the efficiency of the system.

The electricity market in Europe is divided into two main segments, the wholesale market and the retail market. In the wholesale market, buying and selling electricity happens in large quantities and it is principally between generators, suppliers and large consumers. The wholesale market includes transactions between the electric power plants (in the role of electricity producers), large industrial consumers, and traders who purchase electricity to sell in the retail market. Wholesale electricity prices are mostly based on supply and demand, fuel costs, and other market dynamics and vary based on the amount of production. The prices are formed based on the competition between producers on a daily basis. On the other hand, there is the retail electricity market where electricity is sold from traders to end consumers, including households, businesses, and small industries. The retail prices usually include the cost of electricity production (which is linked to the wholesale price), some fees related to the costs of transmission and distribution, and various taxes and levies which vary between European countries. The cost is estimated for each kilowatt-hour (kWh) of consumption and consumers can choose between fixed and variable prices depending on their energy needs and flexibility (Guckian, 2023).

In summary, the historically state-owned companies that managed electricity production gave their places in a single European two-branch market that enhances competition and security of supply. The wholesale electricity market deals with large-scale electricity transactions and price setting, while the retail market focuses on delivering electricity to end consumers with an emphasis on customer service. Both markets are interconnected and play crucial roles in the overall energy system of Europe.

Chapter 3: Electricity profiles of European countries

3.1 Introduction

The purpose of this chapter is to outline an energy profile for a number of European countries by collecting basic information about their electricity production and demand. In addition to all the members of the European Union, the list of countries includes Iceland, Norway and the United Kingdom. Each country's energy "identity" is created by taking into consideration data that include its total installed capacity or its electricity mix; terminologies that were analyzed in the previous chapter.

3.2 Country profiles

3.2.1 Austria

Austria is a landlocked country located in central Europe. It is considered a largely mountainous country as more than three quarters of its total area (of 83,871 km^2) lie in the Eastern Alps. Its estimated population reaches 9.04 million as of 2022.

Austria's electricity sector uses fossil fuels and renewable sources to generate electric power. It mainly imports natural gas and oil to operate its conventional power production facilities and takes advantage of its mountainous relief to generate electricity from hydropower. Renewables like solar, wind and bioenergy power plants have gradually entered Austria's system in the last fifteen years. There are no operating nuclear facilities in the country as the generation of electricity by using nuclear power has been forbidden under its constitution since 1999 (IEA, 2020).

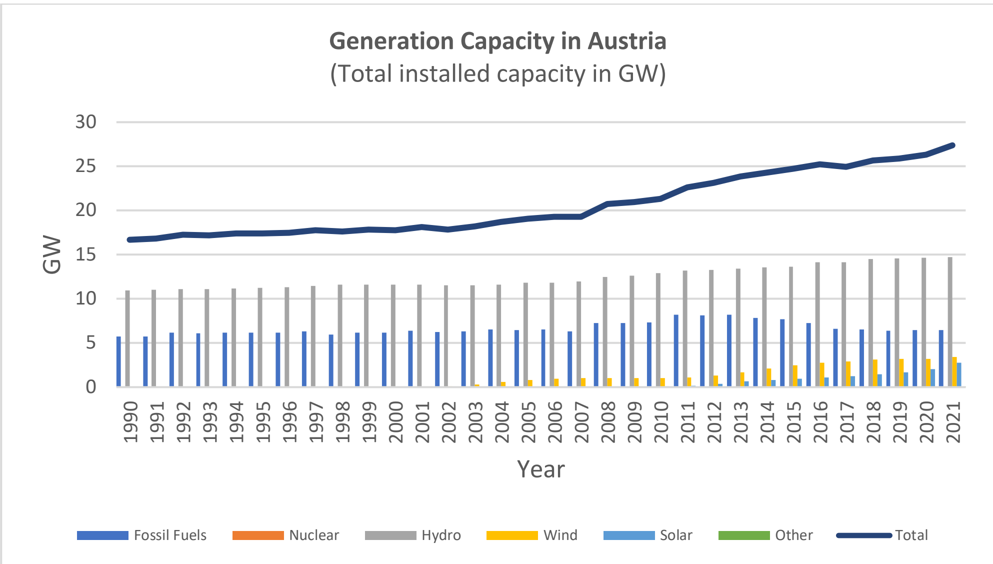

Figure 3.1: Installed capacity by source and total installed capacity in Austria since 1990.

The total generation capacity of the country and the change in the composition of the electricity generation mix since 1990 (based on the source of energy used to produce the electric power) are demonstrated in the following **Figures 3.1** and **3.2** respectively.

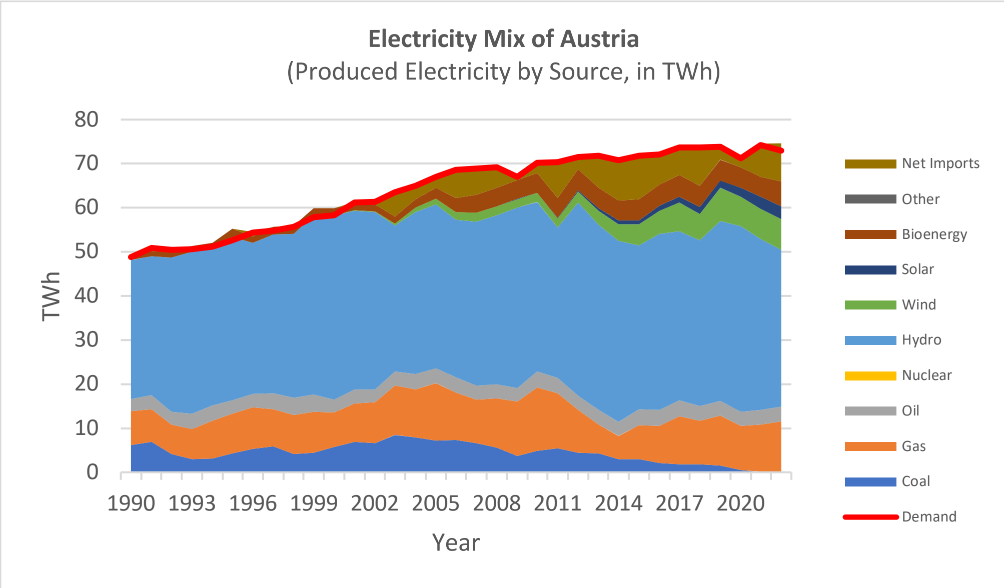

Figure 3.2: Produced electricity by source in Austria since 1990. The red line indicates the electricity demand.

Overall, the electricity sector is characterized by high reliance on renewable sources, as the highest contributing type of energy for electricity generation is hydropower with an ascending rate over the years. The Austrian government has already set a national goal to produce 100 percent of the electricity using solely renewable sources.

3.2.2 Belgium

Belgium is located in northwestern Europe and as of 2022 it has a population of 11.7 million. Its area of approximately 30,690 km^2 borders France, Germany, Luxembourg and the Netherlands and it is washed by the North Sea.

Belgium has a diverse electricity generation system, using a wide range of sources to cover its needs. Fossil fuels occupy a descending percentage while renewables enter the system at a higher speed. However, the main contributor to the electricity mix is nuclear power, with the two nuclear plants of the country producing more than a third of the total electricity. The limited water potential of Belgium keeps the participation of hydropower in low percentages in the mix. The remaining needs are covered by imports from the countries mentioned above, as the country has good interconnection with the neighboring grids.

The national plan is to phase out all the nuclear facilities by 2025 and at the same time achieve zero carbon emissions by 2050 by moving away from fossil fuels. This creates a huge energy gap that needs to be covered by large scale investments in renewable projects like bioenergy, solar and wind power (due to Belgium's proximity to the North Sea, an area of high wind potential).

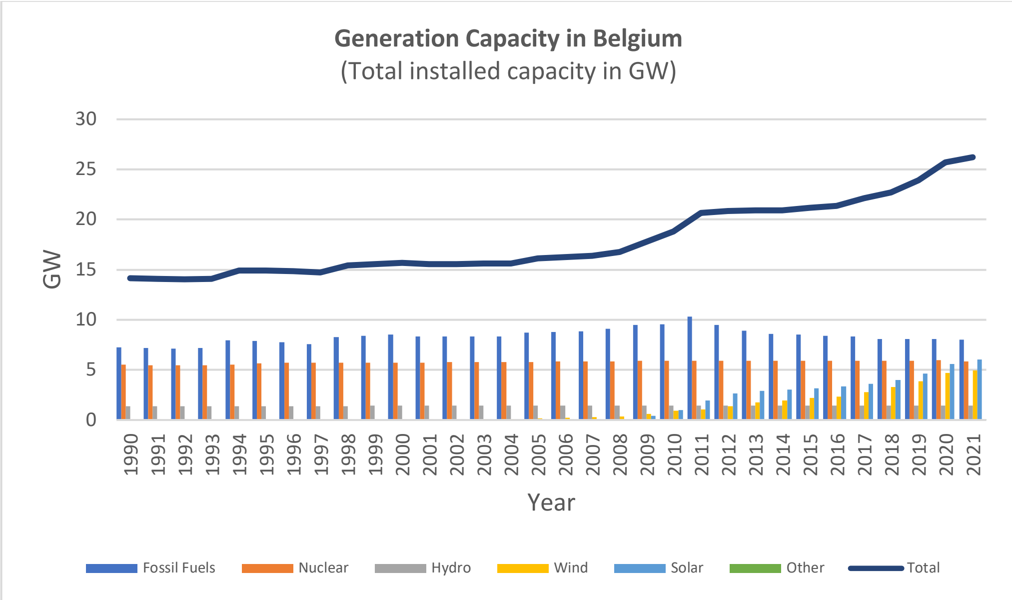

Figure 3.3: Installed capacity by source and total installed capacity in Belgium since 1990.

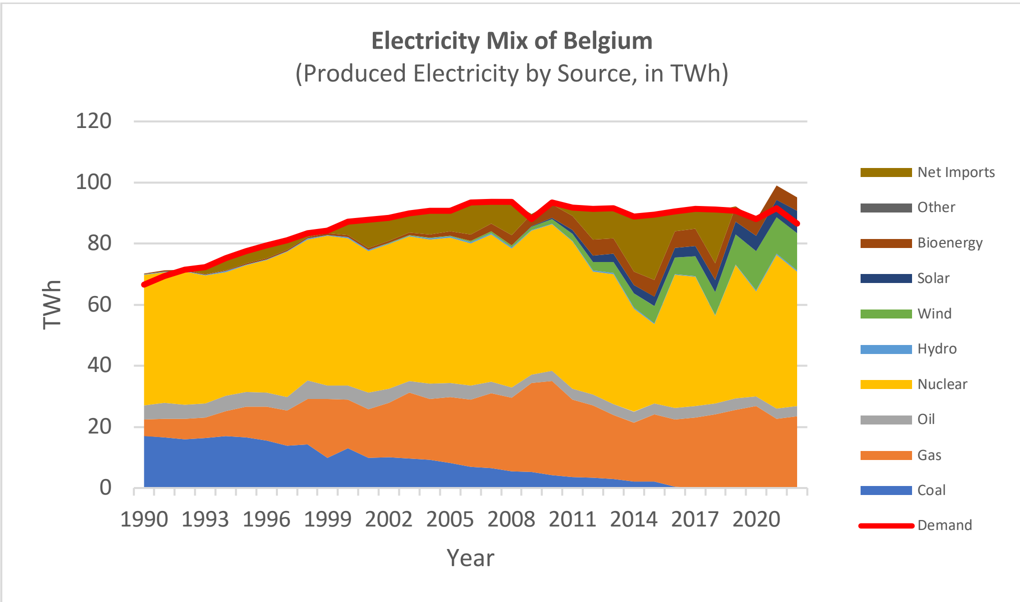

Figure 3.4: Produced electricity by source in Belgium since 1990. The red line indicates the electricity demand.

3.2.3 Bulgaria

Bulgaria is a country of around 110,100 km^2 in southeastern Europe, next to the west coasts of the Black Sea. It is surrounded by North Macedonia and Serbia to the west, Greece and Turkey to the south and Romania to the North and it has an estimated population of 6.5 million as of 2022.

Its energy supply highly depends on two main sources, coal and nuclear power. The two pillars of electricity production, produce together more than two thirds of the total electricity of the country (Bankwatch, 2024). The rest comes from other conventional sources like gas and oil and some renewables with hydropower having the lead.

As demonstrated in **Figure 5**, Bulgaria's generation capacity compared to other European countries, has remained relatively stable over the past 30 years and the total electricity production exceeds the demand as seen in **Figure 6**. Hence, it is a major electricity exporter in the region offering electric power mainly to the nearby markets of Greece, Romania and North Macedonia.

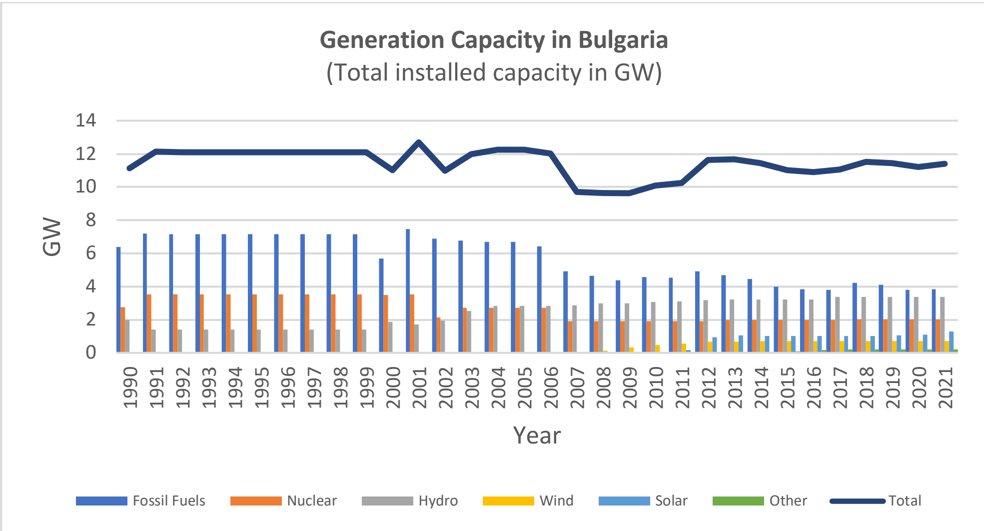

Figure 3.5: Installed capacity by source and total installed capacity in Bulgaria since 1990.

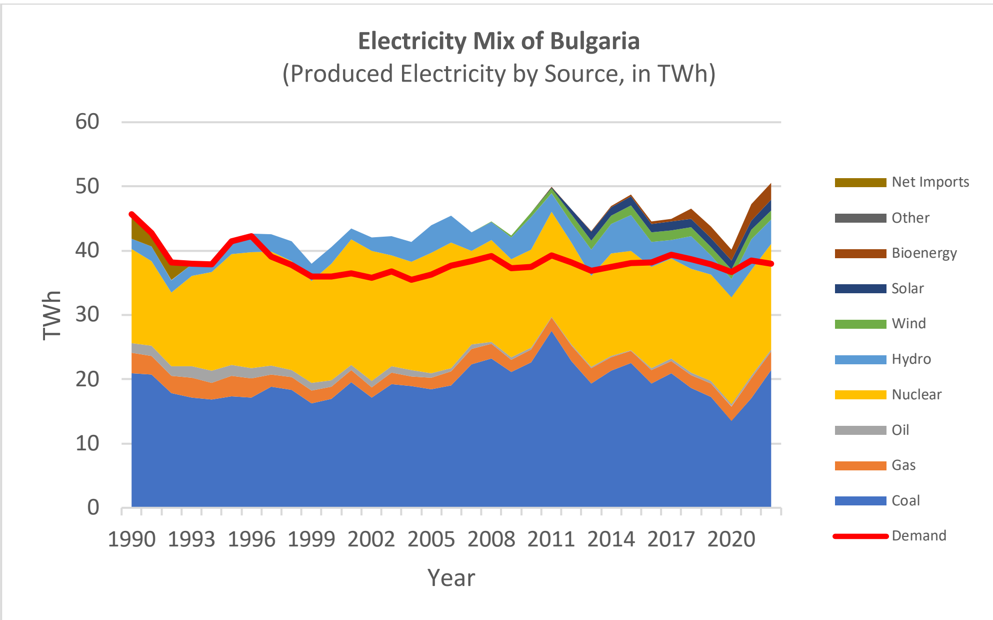

Figure 3.6: Produced electricity by source in Bulgaria since 1990. The red line indicates the electricity demand.

Bulgaria, unlike most European countries, continues to rely on fossil fuels' plants for a large part of its electricity production, without short term plans for termination of their operation and with the renewables occupying only a small part of the energy mix. Despite this, it still has the obligation to achieve specific low carbon emission goals that are established by the European Union, in the near future.

3.2.4 Croatia

Located in central eastern Europe, Croatia is a country covering an area of 56,600 km^2 with a population of almost 3.8 million inhabitants (as of 2022 estimates). It is a member state of the European Union since 2013.

Electricity in the country is characterized by a diverse production mix that includes both fossil fuels and renewable sources of energy. Conventional power plants operate mostly by using coal and natural gas, while at the same time hydropower is the largest renewable source of energy in the country. Croatia is strongly dependent on electricity imports from the neighboring countries, as it has a state of the art and well-integrated international grid, and although there are no nuclear plants in the country, it indirectly uses nuclear power by importing electricity produced by the nearby Slovenia's facilities.

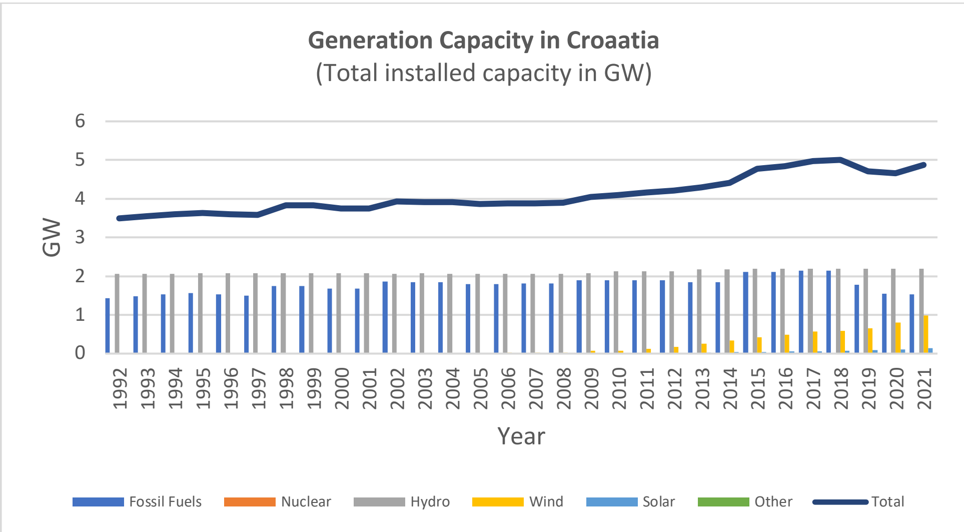

Figure 3.7: Installed capacity by source and total installed capacity in Croatia since 1992.

Croatia's energy policy, aligned with European Union's goals for low carbon emissions, includes moving away from combustible fuels and expanding renewable electricity projects and especially wind and solar projects -as hydropower is already used extensively- by increasing their total generation capacity and their participation to the mix.

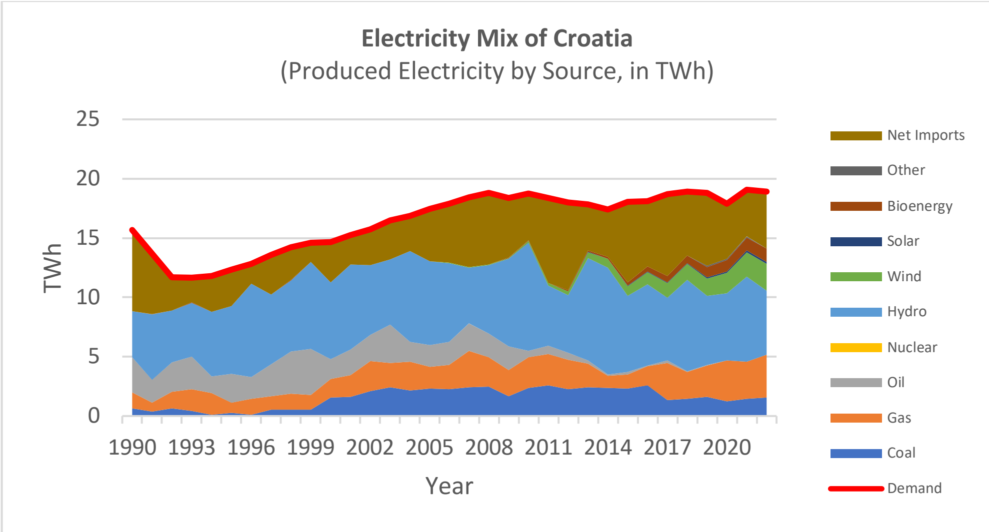

Figure 3.8: Produced electricity by source in Croatia since 1990. The red line indicates the electricity demand.

3.2.5 Cyprus

Cyprus is an Island country of the eastern Mediterranean close to the coasts of Asia. With an area of 9,251 km^2 and with almost 1 million inhabitants, it is the third largest island of Mediterranean Sea both in size and in terms of population.

Until the early 2010s the total amount of electric power on the island was produced by fossil fuels, as thermal power stations that run on oil were the only operating facilities as shown in **Figure 9**. Neither nuclear plants nor hydroelectric power stations exist in the country. In terms of other renewables, only wind and solar power plants have entered the system in the past decade and a tiny percentage of the generation mix (**Figure 10**) comes from the use of biofuels too.

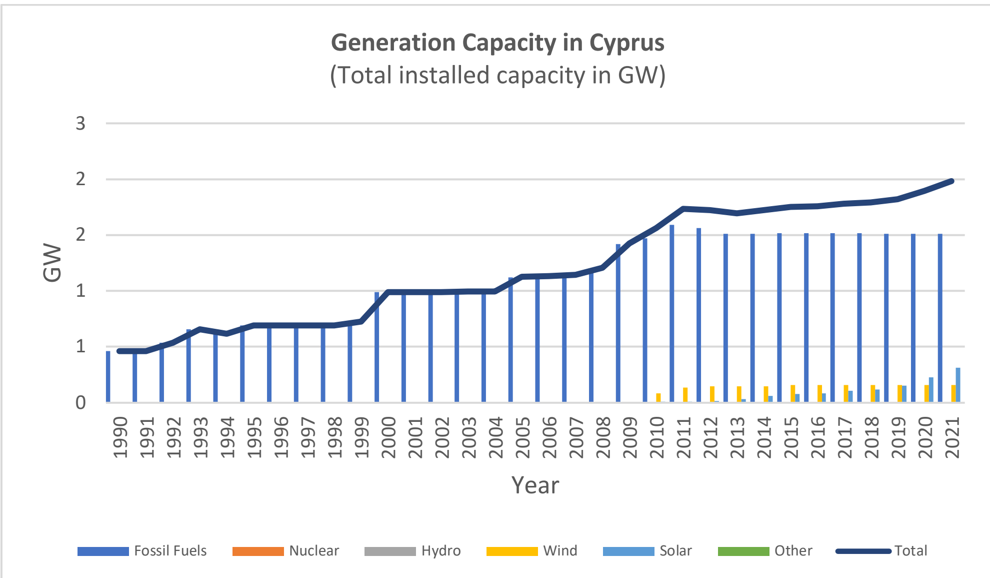

Figure 3.9: Installed capacity by source and total installed capacity in Cyprus since 1990.

The challenges that the electricity management of Cyprus faces, include the lack of interconnections with no ability for imports, the potential dangers of its large dependence on oil; those factors make it vital for the island to attract investments in renewable sources.

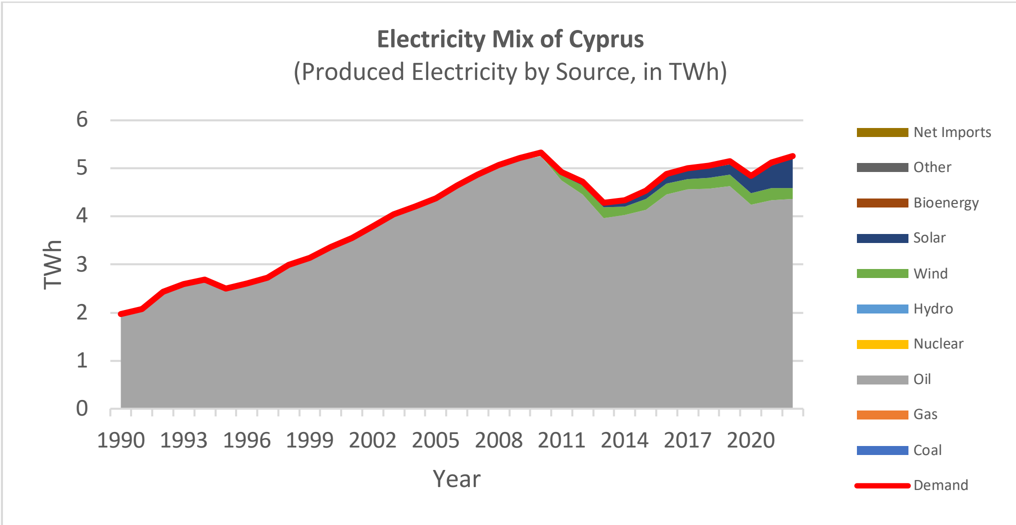

Figure 3.10: Produced electricity by source in Cyprus since 1990. The red line indicates the electricity demand.

3.2.6 Czech Republic

Czech Republic is a landlocked country in central Europe between Austria, Germany, Poland and Slovakia. It covers an area of almost 78,900 km^2 while its population reaches almost 10.5 million inhabitants as of 2022.

The electricity sector of the country uses a variety of primary energy sources and has a diverse generation mix as demonstrated in **Figure 12**. Its main contributors are lignite (coal) and nuclear power which combined produce almost 80% of the total electricity today. Renewables like wind, solar and especially bioenergy have entered the system the last fifteen years, while the use of hydropower has remained steady since 1990. The total generation capacity showed an increase during the 90s and the 00s but has remained relatively stable the past decade as seen in **Figure 11**.

Czechia’s electricity production exceeds the total demand, making the country an exporter in the region, trading with all the neighboring countries that were mentioned above. The national plans to gradually phase out the country’s conventional power facilities, has led to the introduction of renewable sources like bioenergy and variables (solar and wind power), and at the same time the government intends to increase the generation capacity of the nuclear plants and their participation to the mix.

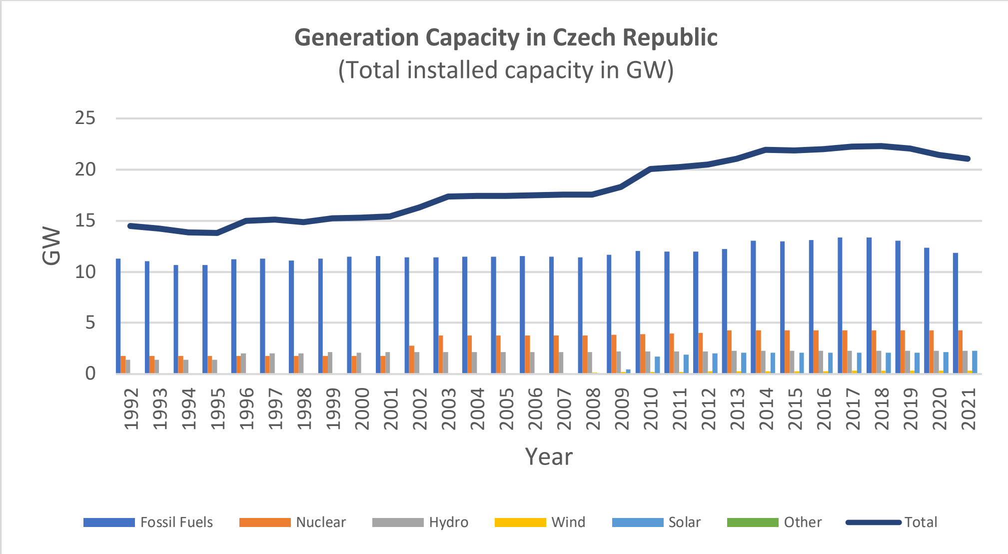

Figure 3.11: Installed capacity by source and total installed capacity in Czech Republic since 1992.

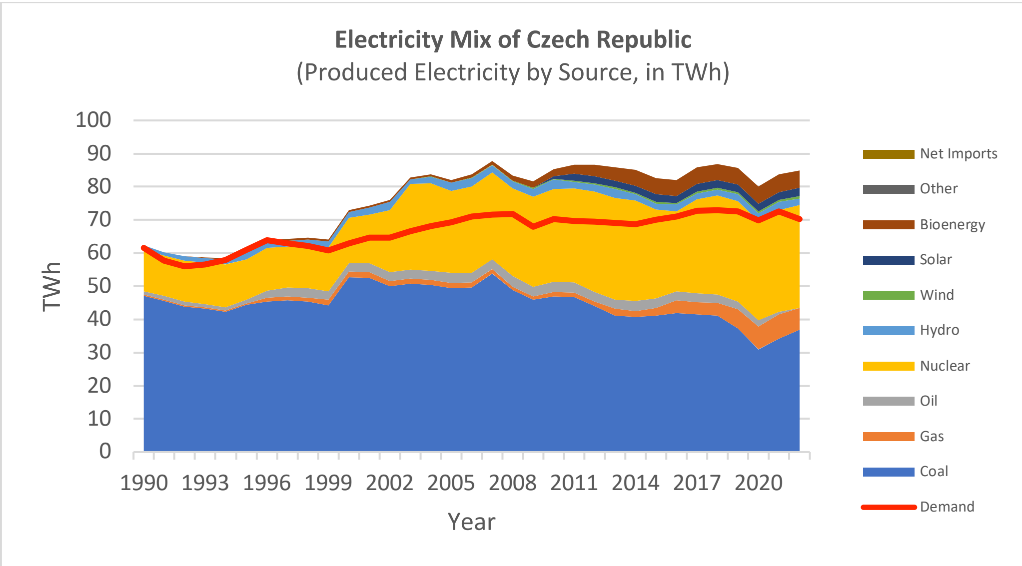

Figure 3.12: Produced electricity by source in Czech Republic since 1990. The red line indicates the electricity demand.

3.2.7 Denmark

Denmark is a country covering about 43,000 km^2 located in northern Europe and has a population close to 6 million (in 2022). It is a peninsula surrounded by the North Sea in the west and the Baltic Sea in the east, and it only borders Germany in the south.

Electricity production in Denmark is known for its extensive use of renewable primary sources and especially wind power which today generates more than half of the total electricity and covers almost 50% of the total capacity in the country as we can see in **Figures 13** and **14**. Other sources include fossil fuels, with coal being the primary source of production in the 90s and the 00s, solar power and biofuels.

Denmark is generally a net importer today compared to the past, when it exported the surplus of its production to the neighboring countries. Its electricity system is a model of successful insertion of the renewables to the electricity generation process while at the same time it continues to reinforce the infrastructure and secure its power supply.

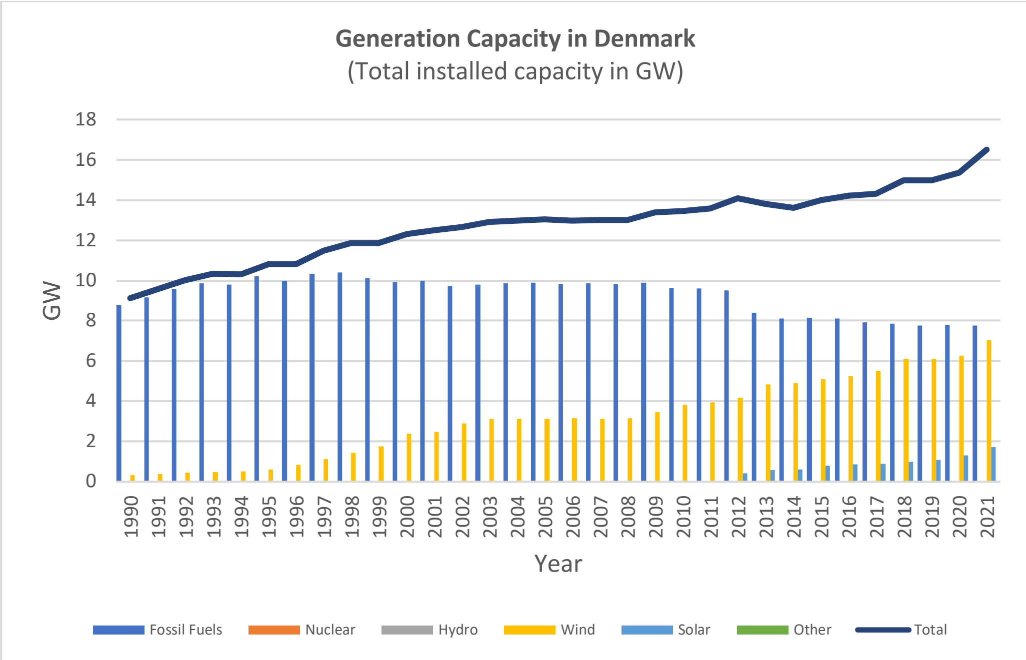

Figure 3.13: Installed capacity by source and total installed capacity in Denmark since 1990.

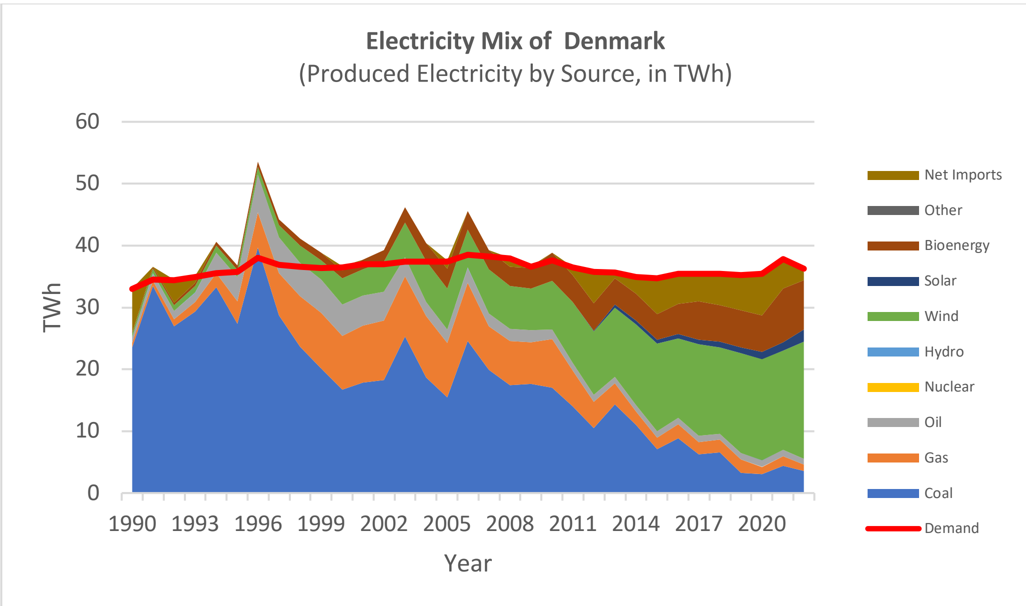

Figure 3.14: Produced electricity by source in Denmark since 1990. The red line indicates the electricity demand.

3.2.8 Estonia

Estonia, the northernmost of the three Baltic countries, lies in Northern Europe by the shores of the Baltic Sea. It covers an area of 45,335 km^2 and it has almost 1.4 million inhabitants.

The electricity production in Estonia highly depends on fossil fuels and most specifically on oil shale, the source that covered most of the demand until the late 2010s. There have been significant efforts to add renewable generation capacity in the system in the last decade, and now solar and wind power plants, as well as biofuels contribute to the electricity generation in a proportion that has already doubled its size.

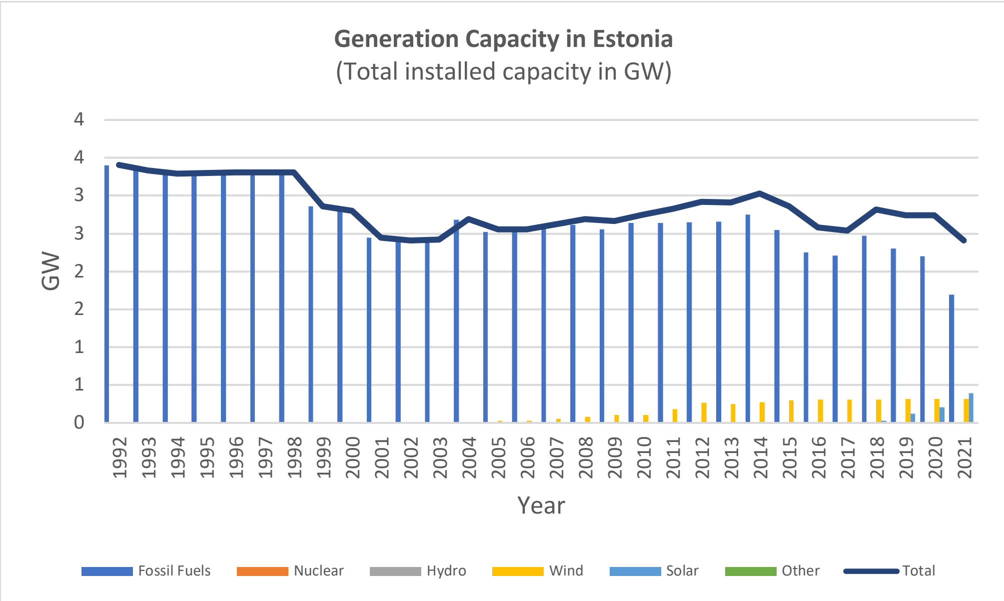

Figure 3.15: Installed capacity by source and total installed capacity in Estonia since 1992.

The electricity sector in the country is undergoing significant changes, as the national plan targets to 100% renewable electricity by 2030. Additionally, taking into consideration the gradual decommission of conventional facilities, the growing demand, and the fact that Estonia takes a shift from a net exporter to an importer, the management of the production faces large challenges.

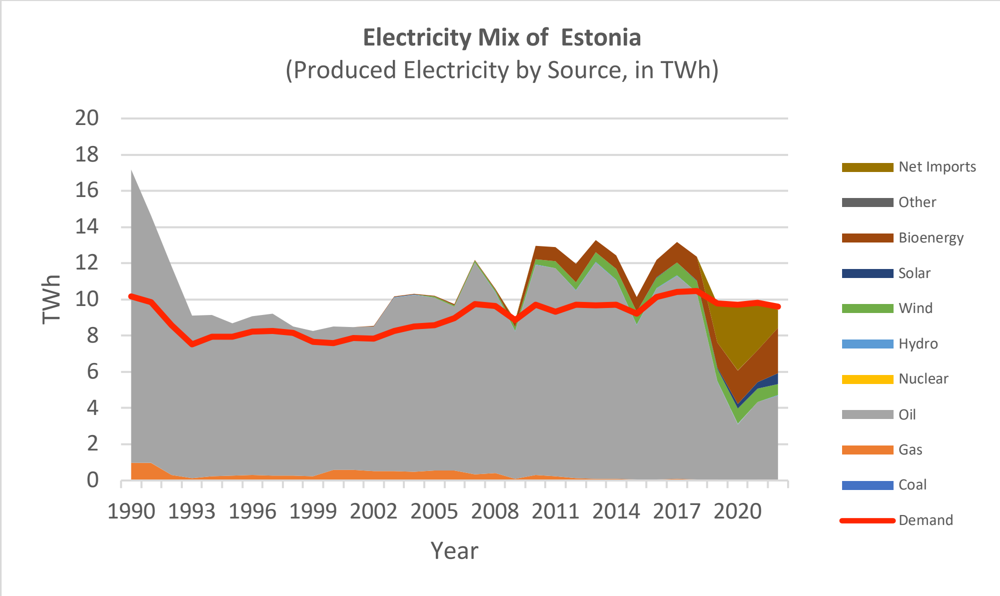

Figure 3.16: Produced electricity by source in Estonia since 1990. The red line indicates the electricity demand.

3.2.9 Finland

Covering an area of more than 338,000 km^2, Finland is located in northern Europe, and it has a population of 5,6 million (according to 2022 estimates).

Overall, Finland is considered a net importer of electricity. To cover the demand, Finland imports the deficit of electric power from the neighboring Nordic and Baltic countries and as well as from its interconnections with Russia.

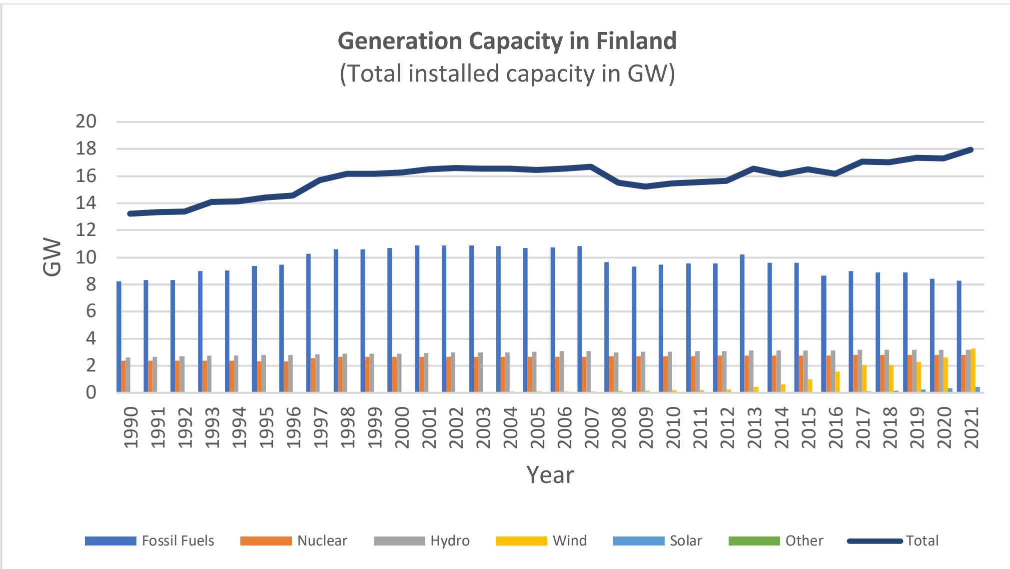

Figure 3.17: Installed capacity by source and total installed capacity in Finland since 1990.

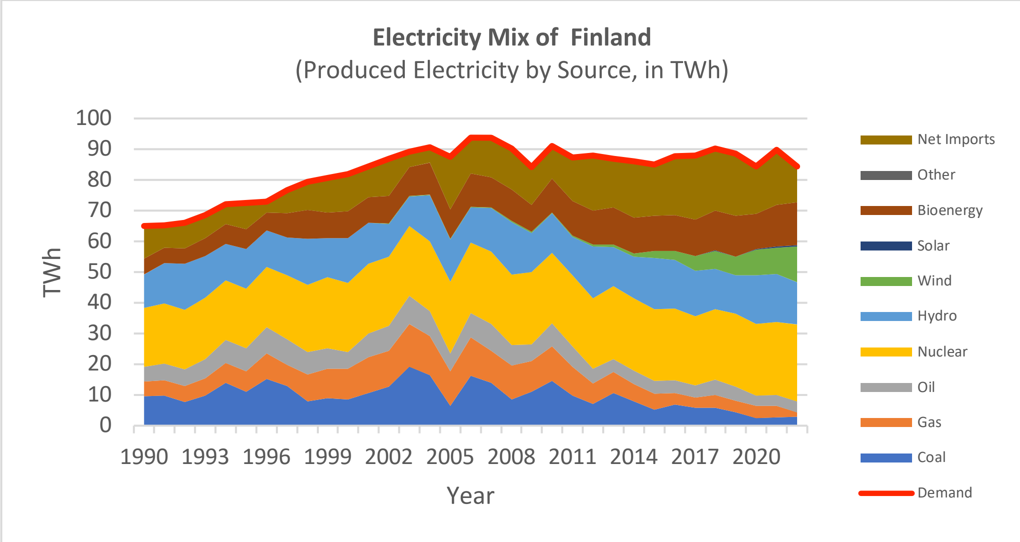

Figure 3.18: Produced electricity by source in Finland since 1990. The red line indicates the electricity demand.

The electricity in the country is produced using a wide range of primary energy sources including combustible fuels, renewables, and nuclear power. Its nuclear installed capacity of almost 2.8 GW (as of 2021), has remained stable since 1990 and it is responsible for one third of the total electricity production in the country. The use of conventional sources in the mix has shown a significant decline over the past years, as they are gradually replaced by renewables; wind power capacity grows rapidly day after day thanks to the government's favorable policies on these investments, while Finland's vast forest lands are important bioenergy resources. Lastly, hydropower participates at a respectable percentage to the generation mix.

3.2.10 France

With an area of 551,700 km^2 and a population of more than 66 million people, France is one of the largest countries in Europe both in terms of size and population. Its main land body is in western Europe, although it has under its sovereignty many overseas regions and territories all around the world.

The electricity sector in France is characterized by the dominance of nuclear power, as its plants produce more than 70% of the total electricity in the country, making it by far the largest nuclear power producer in the world. Hydroelectric power is the second largest electricity source at a national level, while other renewables and a small proportion of fossil fuels complete the mix. The total generation surpasses the demand making France a major exporter in the region of central and western Europe.

France's energy sector, which thanks to nuclear power already offers low carbon electricity for years, predicts full decommission of the few remaining conventional plants by the early 2020s, and participation of more renewable power facilities in the total capacity of the system.

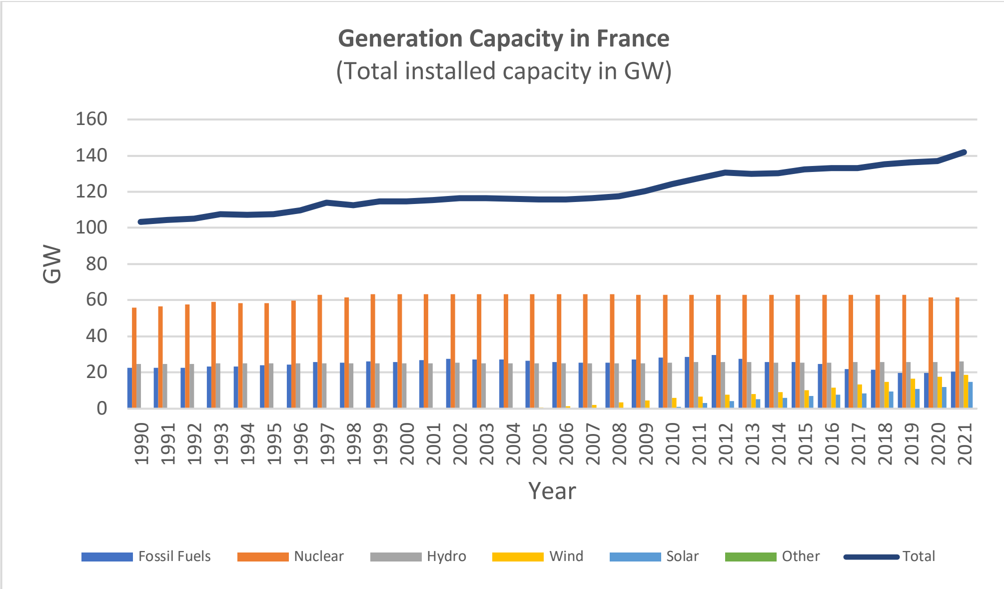

Figure 3.19: Installed capacity by source and total installed capacity in France since 1990.

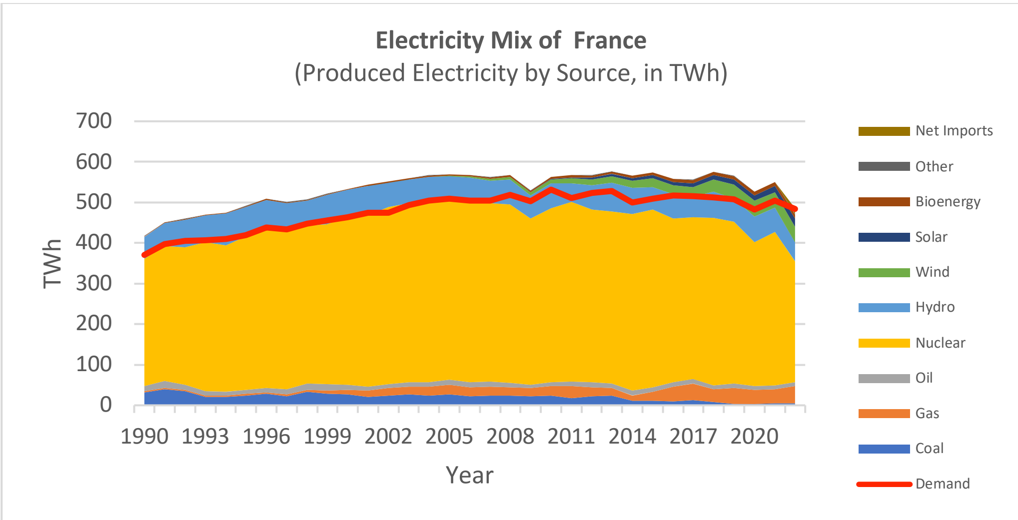

Figure 3.20: Produced electricity by source in France since 1990. The red line indicates the electricity demand.

3.2.11 Germany

Located in central Europe, Germany is the most populous country of the European Union, with more than 84 million inhabitants as of 2022. It covers an area of 357,600 km^2, and it shares borders with many other countries in the central Europe.

Germany's electricity sector is right now one of the largest and most advanced in the world, as it needs to ensure sufficient supply to the country's households and most importantly to its heavy industry. The generation mix is composed by a wide variety of conventional and renewable sources, as well as nuclear power. Until the early 2020s, the major source of electricity is coal, generating more than a third of the total production followed by nuclear and other combustibles. Electricity from hydropower is produced in a small and relatively constant amount since 1990. The total generation overpasses the demand, making Germany an exporter in the region.

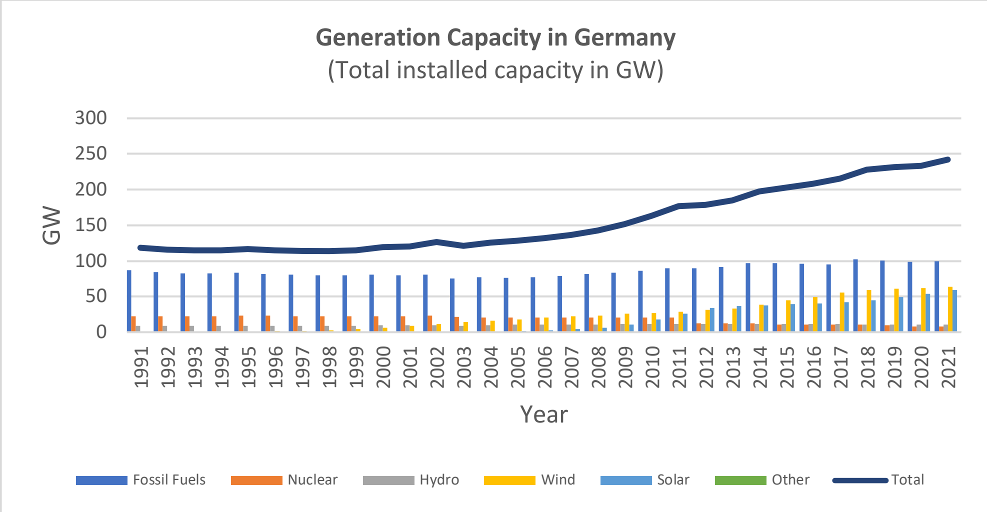

Figure 3.21: Installed capacity by source and total installed capacity in Germany since 1991.

The total generation capacity of the system continuously increases even though the demand for electricity has remained stable since 2000. The energy policy followed by the government, includes shutting down all nuclear facilities by 2024 and coal power plants in the next 10 to 15 years, in an effort to make a transition to more clean sources of electricity. Hence, Germany is investing in renewables like biomass, solar and especially wind power, which has quickly taken the second place in the composition of the mix.

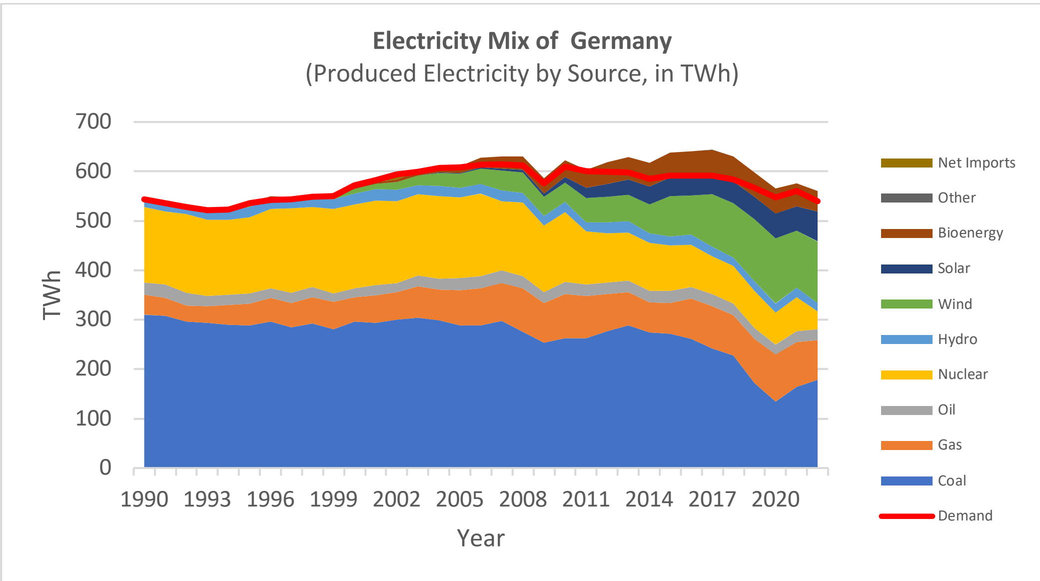

Figure 3.22: Produced electricity by source in Germany since 1990. The red line indicates the electricity demand.

3.2.12 Greece

Located on the tip of the Balkan peninsula, Greece is a country in southeastern Europe, covering an area of 132,000 km^2 and with a population of about 10.6 million as of 2022.

The electricity produced in the country, comes from a variety of sources including fossil fuels and many renewables. For many years, lignite (a type of coal) was the dominant source of electric power in the country, with oil and natural gas participating in large quantities in the mix too. Large hydroelectric power facilities are operating, usually covering the demand during the peak hours, while wind and solar plants -that take advantage of the large wind and solar potential of the country- have gained in popularity since the 2000s and 2010s respectively. As demonstrated in **Figure 23**, the total capacity of the system is constantly growing and has doubled in size the last 30 years, even though the electricity demand has a visible decline since 2009 (**Figure 24**).

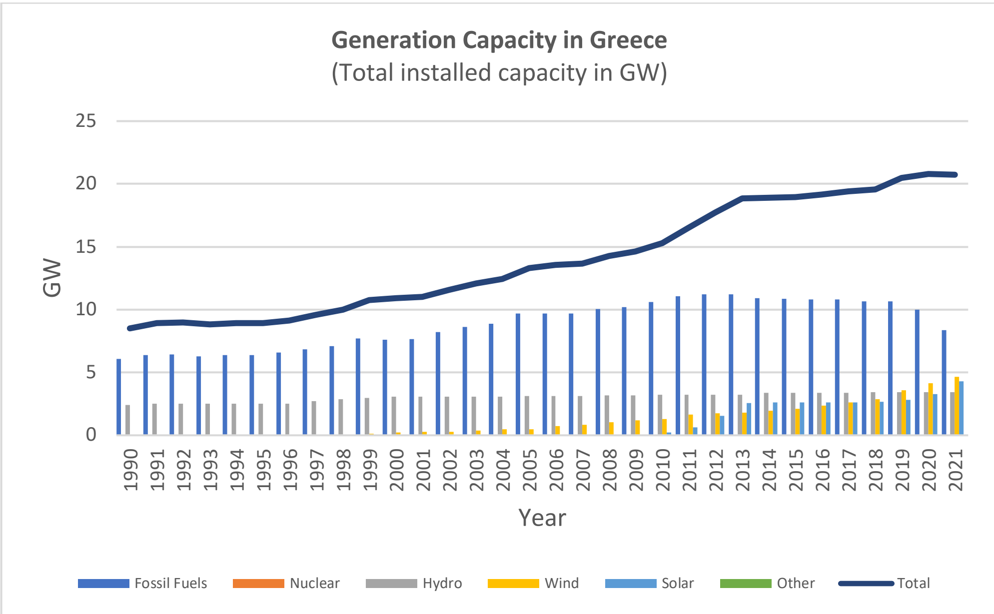

Figure 3.23: Installed capacity by source and total installed capacity in Greece since 1990.

Greece's electricity system is undergoing significant changes. It is continuously adding facilities running on renewables to the mix, and the government aims to shut down all the lignite power plants of the country by 2028, complying in that way with the common EU policies on clean energy and electric power from sustainable and low emission sources.

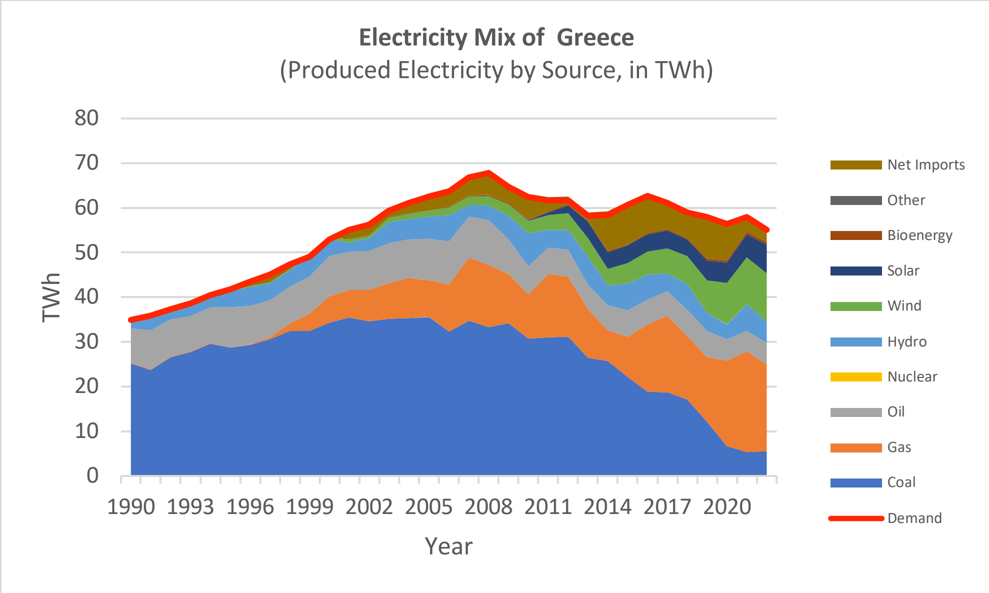

Figure 3.24: Produced electricity by source in Greece since 1990. The red line indicates the electricity demand.

3.2.13 Hungary

Hungary is a country in central Europe, with an area of around 93,000 km^2 and approximately 9.6 million inhabitants.

The electricity supply in Hungary, comes from a range of primary energy sources from fossil fuels to nuclear power and renewables. The largest amount of electric power originates from the country's only nuclear facility, while coal and natural gas have a considerable presence in the mix. Renewables like bioenergy and solar power develop constantly, resulting in the rapid ascend of the system's total generation capacity.

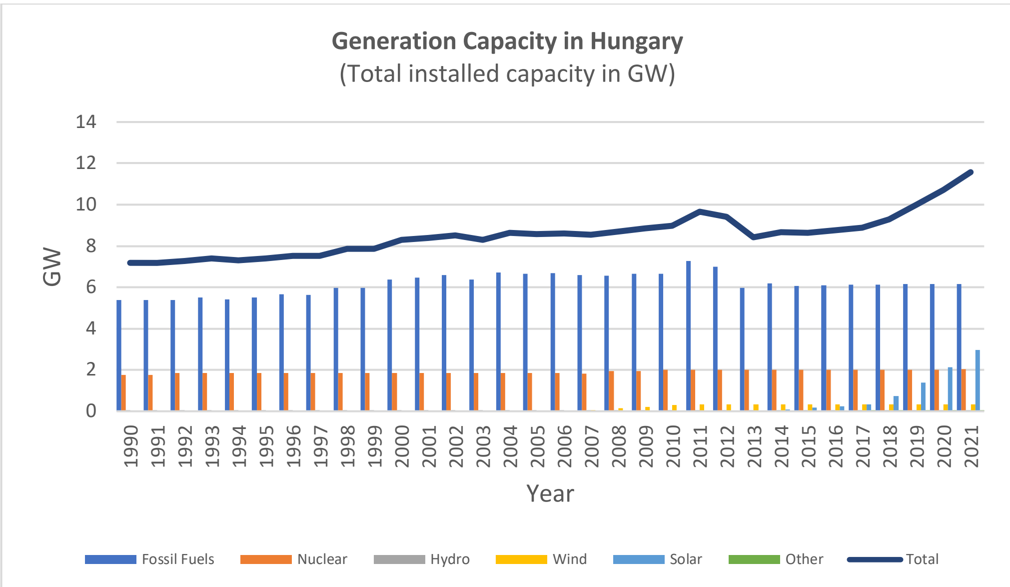

Figure 3.25: Installed capacity by source and total installed capacity in Hungary since 1990.

Hungary heavily relies on incoming electricity from the neighboring countries to cover the deficit in its total demand. During the last decades, and because the country joined the European Union in 2004, the electricity sector of Hungary has undergone great changes. The national policy is now orientated toward composing a more sustainable power mix, by phasing out conventional power plants and investing in even more renewables, restraining at the same time the country's large dependency on imported electric power.

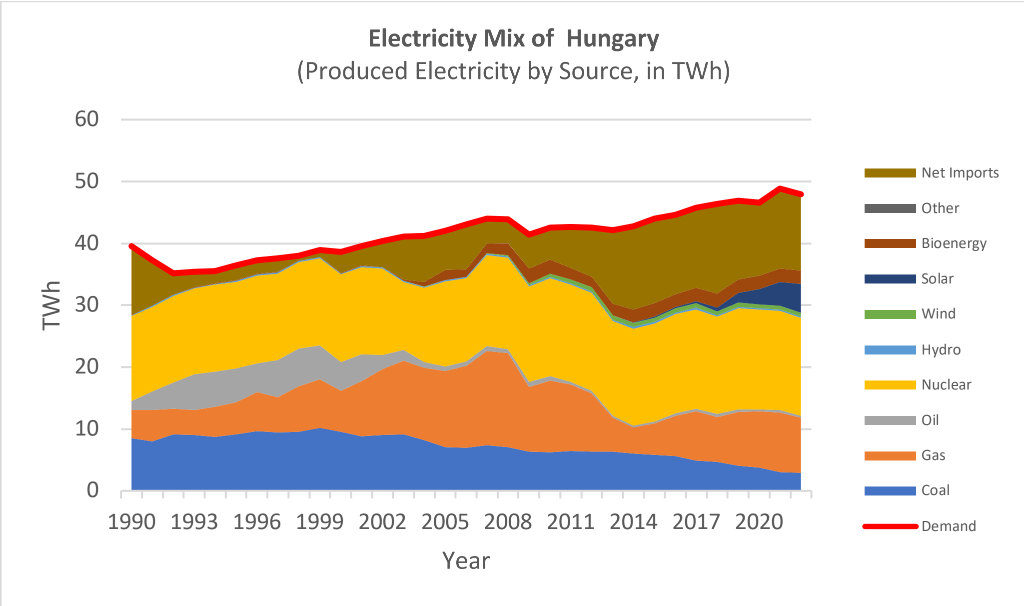

Figure 3.26: Produced electricity by source in Hungary since 1990. The red line indicates the electricity demand.

3.2.14 Ireland

The Republic of Ireland is an island country located in northwestern Europe. It covers the southern part of the homonymous island as it borders to the north with Northern Ireland (which is part of the United Kingdom). The total area of the country is 70,273 km^2 and its population is 5.3 million based on 2022 estimates.

The main source of electric power is natural gas, which produces half of the electricity in the island, while other combustibles like oil and coal are present in the mix. Hydropower is used in small and fixed quantities since 1990. Other renewables like wind and solar are growing at an impressive rate, and wind power specifically has more than doubled -both in terms of total capacity and in terms of generation- during the past decade, becoming today the second largest source of electricity in the country. At the same time, Ireland's interconnected grid to the United Kingdom, covers the supply during a potential increase in the demand.

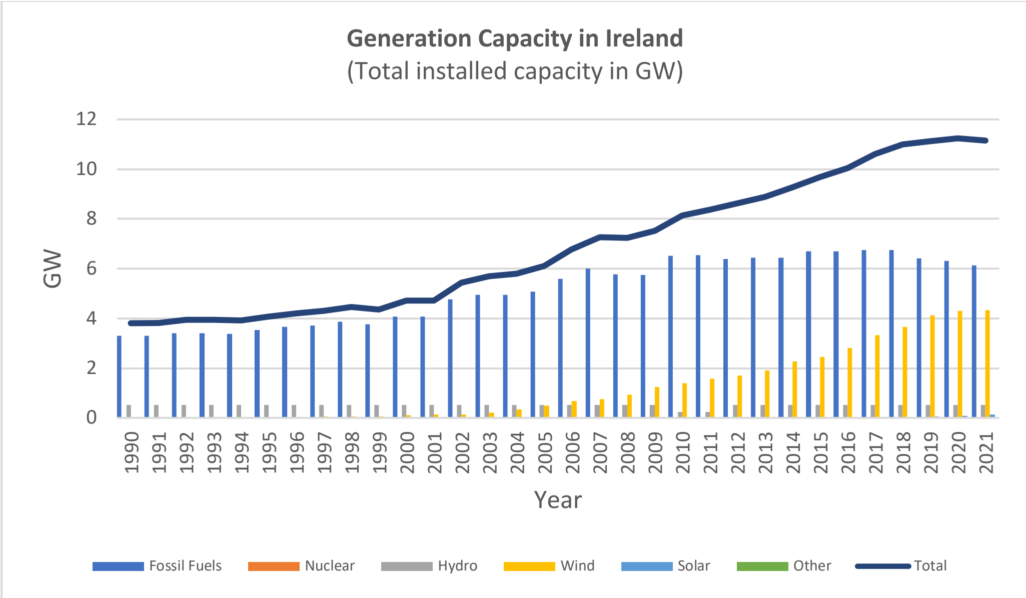

Figure 3.27: Installed capacity by source and total installed capacity in Ireland since 1990.

The energy strategy followed by the country, predicts further increase in the renewable capacity of the system, and aims to gradually reduce the use of conventional sources in the future.

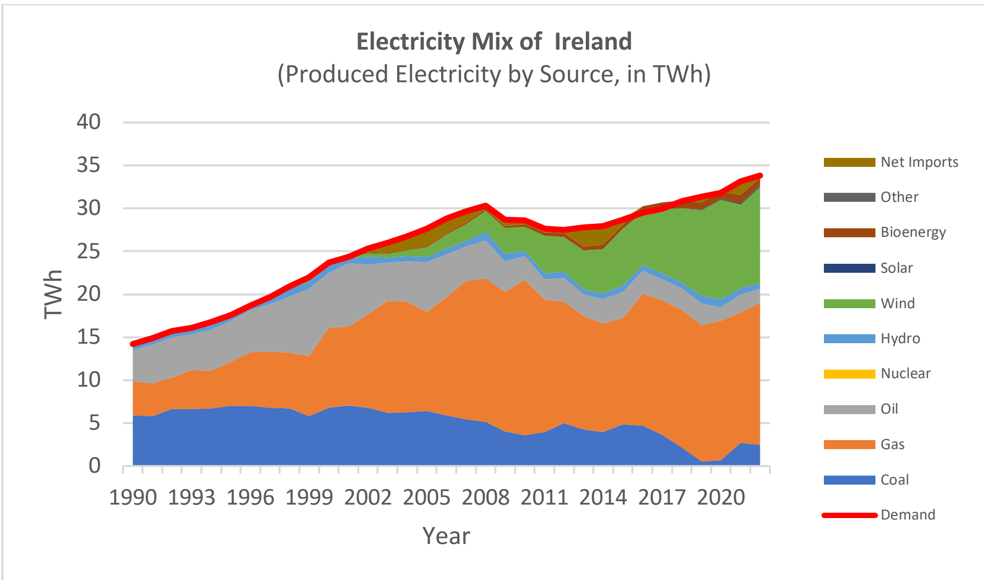

Figure 3.28: Produced electricity by source in Ireland since 1990. The red line indicates the electricity demand.

3.2.15 Italy

Italy is located in southern Europe, forming a peninsula that is surrounded by the Mediterranean Sea, and it borders the mountain range of the Alps to the north. It is one of the most populated countries of Europe with about 58.8 million inhabitants and covers an area of 301,340 km^2.

Italy's electricity mix heavily relies on fossil fuels and especially natural gas, which produces the largest amount of electric power in the country, with coal and oil having significantly reduced their total participation to the mix during the last years. Electricity from hydropower plays an important role as it is the most used clean energy source, produced in large scale hydroelectric plants, that are usually situated in the alpine landscape in the northern part of the country. Wind and solar power follow in an ascending rate while a small percentage of the generation capacity is represented by biofuels and some geothermal facilities. There are no nuclear power plants in the country.

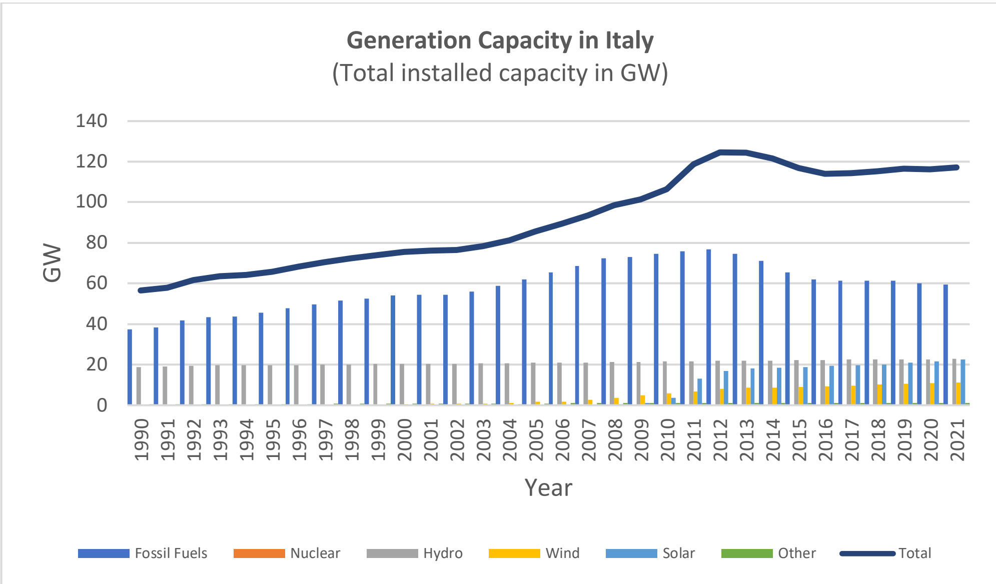

Figure 3.29: Installed capacity by source and total installed capacity in Italy since 1990.

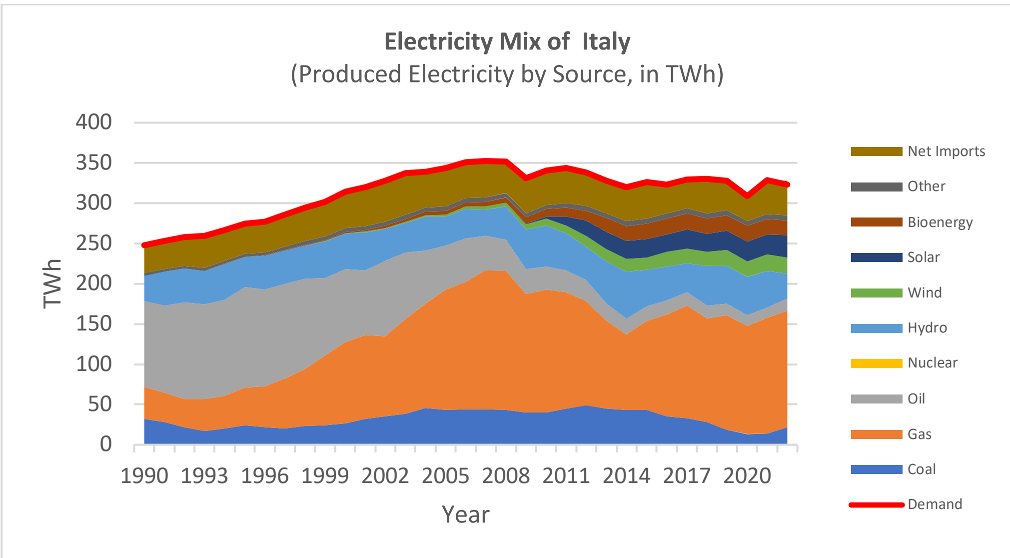

Figure 3.30: Produced electricity by source in Italy since 1990. The red line indicates the electricity demand.

Overall, the electricity sector of Italy uses a wide variety of sources to generate electricity and trades it -as a net importer- via a well interconnected grid with the countries of central and southern Europe. Aligned with the most European energy policies, Italy has already set decarbonization targets, that are gradually achieved by the limitation in the use of combustible fuels and the investments on more sustainable and clean energy sources.

3.2.16 Latvia

With a population of 1.9 million people, Latvia is a country of northern Europe covering an area of about 64,600 km^2. It is one of the Baltic countries together with Estonia and Lithuania, lying between the two, by the shores of the Baltic Sea.

The electricity mix in the country mainly consists of hydropower and natural gas and a large amount of the necessary electricity is imported from the neighboring Baltic countries, Russia and Belarus. The hydropower facilities that cover the production include three large plants and much smaller ones. Renewables like biofuels and wind power have gained in popularity from 2010s and onwards, while the installed capacity of solar power still remains at zero levels. There are also no nuclear facilities in the country.

The energy policy of the country aims to create interconnections with the rest of the countries of the EU in the area, in order to reduce its dependence on Russian and Belarusian electricity imports. At the same time, the government promotes investments in renewables, in an effort to take a turn towards a greater sustainability in the process of electricity generation.

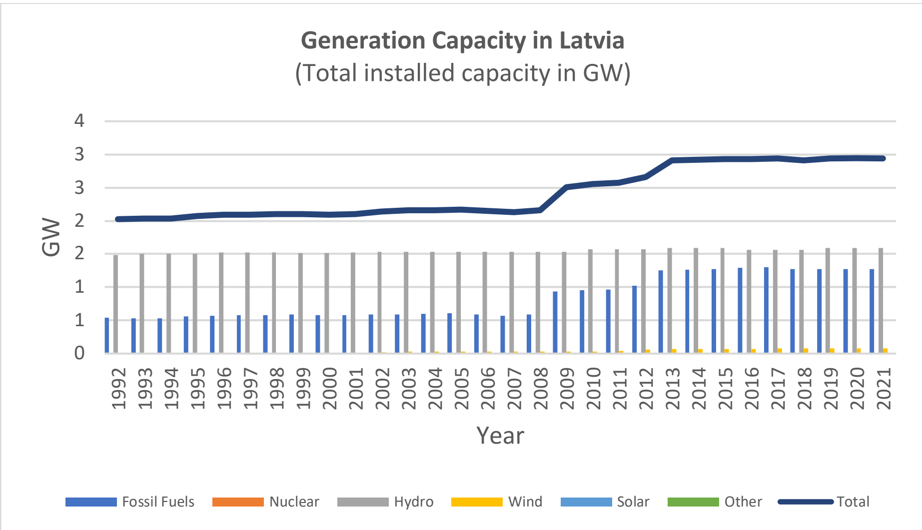

Figure 3.31: Installed capacity by source and total installed capacity in Latvia since 1992.

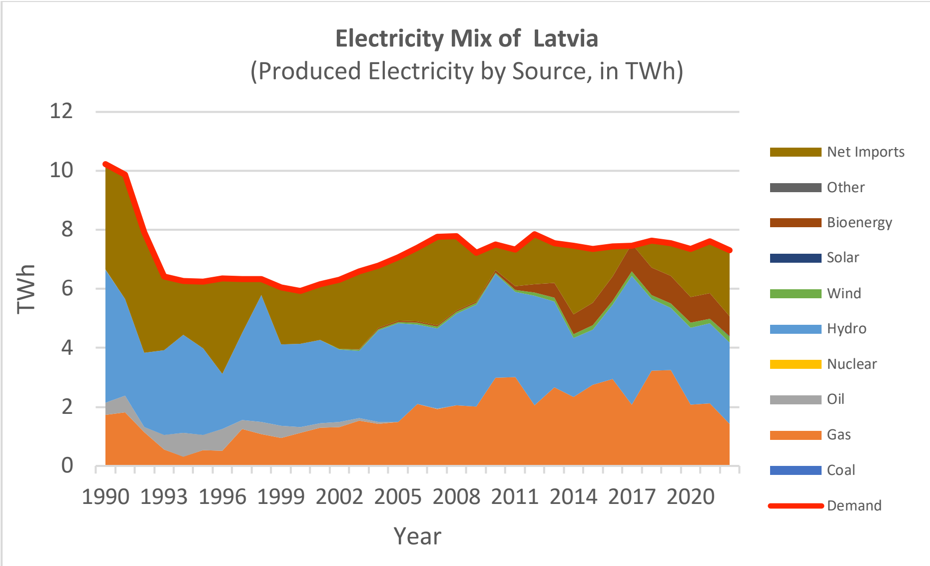

Figure 3.32: Produced electricity by source in Latvia since 1990. The red line indicates the electricity demand.

3.2.17 Lithuania

Lithuania, the southernmost of the three Baltic countries, lies in Northern Europe by the shores of Baltic Sea. It covers an area of 45,335 km^2 and it has almost 1.4 million inhabitants.

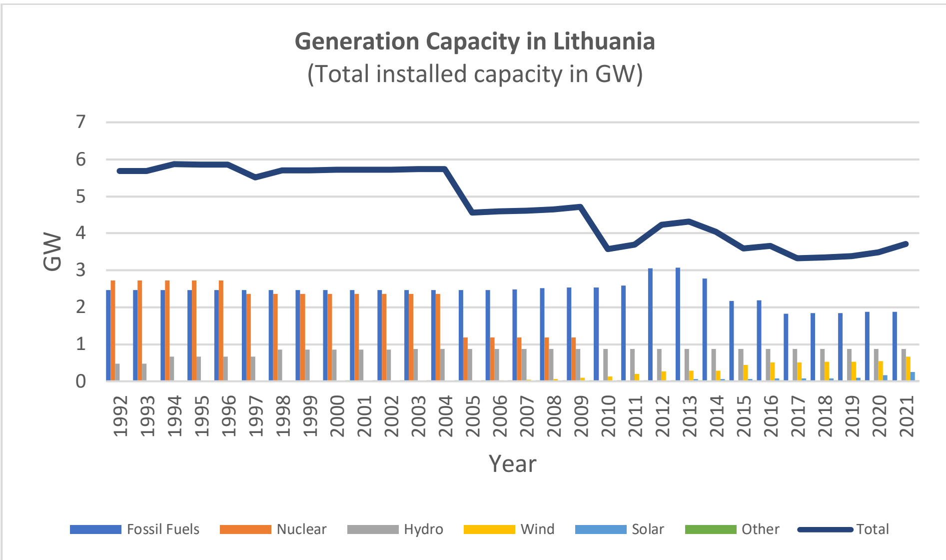

Figure 3.33: Installed capacity by source and total installed capacity in Lithuania since 1992.

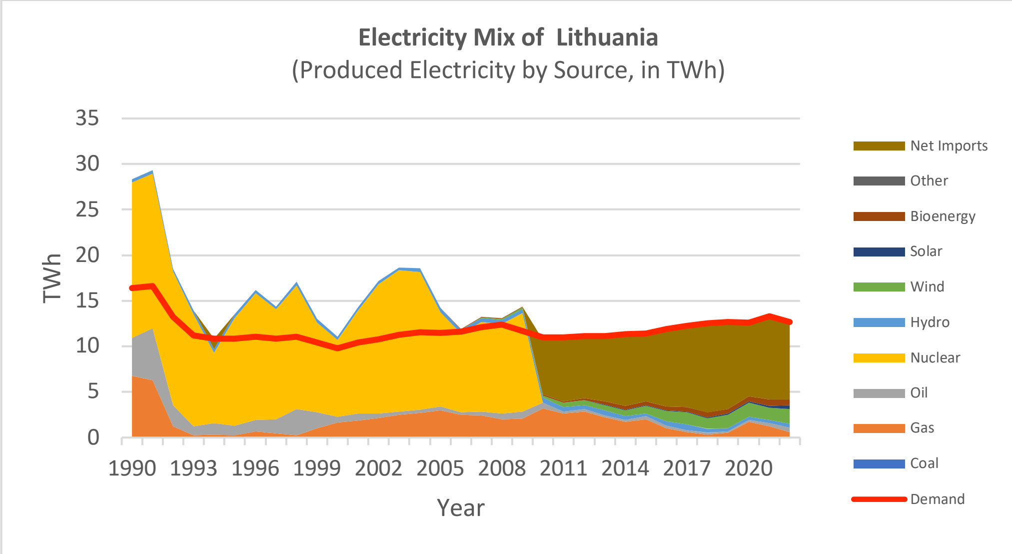

Figure 3.34: Produced electricity by source in Lithuania since 1990. The red line indicates the electricity demand.

For a long time, electricity production in Lithuania relied on nuclear power, as most of its generated electricity came from the county's only nuclear plant. With the closing of the plant in 2009, most of the total generation capacity was lost and the remaining production came from fossil fuels (mainly gas) and renewables. Consequently, Lithuania changed from being a major exporter in the Baltic area to being a net importer in order to cover the demand. Since then, the country has replaced a part of the total generation with the installation of more renewables; mainly wind power and biofuels. Hydropower has maintained the same capacity since late 1990s and it uses it only for demand peaks.

The electricity sector has undergone great changes in recent years, as Lithuania is one of the few European countries to alternate its energy policy from importer to exporter and at the same time, it moves from a nuclear power-based system to a renewable based, by creating mainly new wind and bioenergy power facilities.

3.2.18 Luxembourg

Located in western Europe, Luxembourg is a small country that covers an area of just 2586 km^2 between Belgium, France and Germany. Its small population reaches 650,000 inhabitants as of 2022.

The electricity generation in the country happens in a much small scale compared to its neighbors. Regarding its small size, Luxembourg is highly dependent on electricity imports to cover its demands. However, its system's generation capacity includes some natural gas, small run on the river hydroelectric plants, biomass plants and an increasing proportion of wind and solar. Luxembourg intends to remain a net importer of electricity in the future but also aims to invest in renewable primary energy sources, in order to generate on its own cleaner electricity.

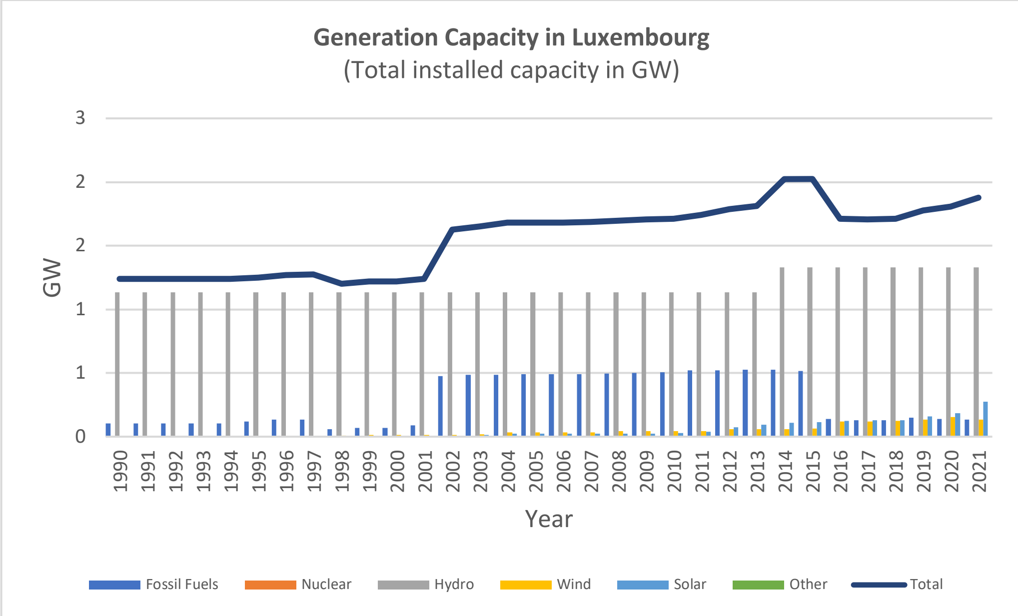

Figure 3.35: Installed capacity by source and total installed capacity in Luxembourg since 1990.

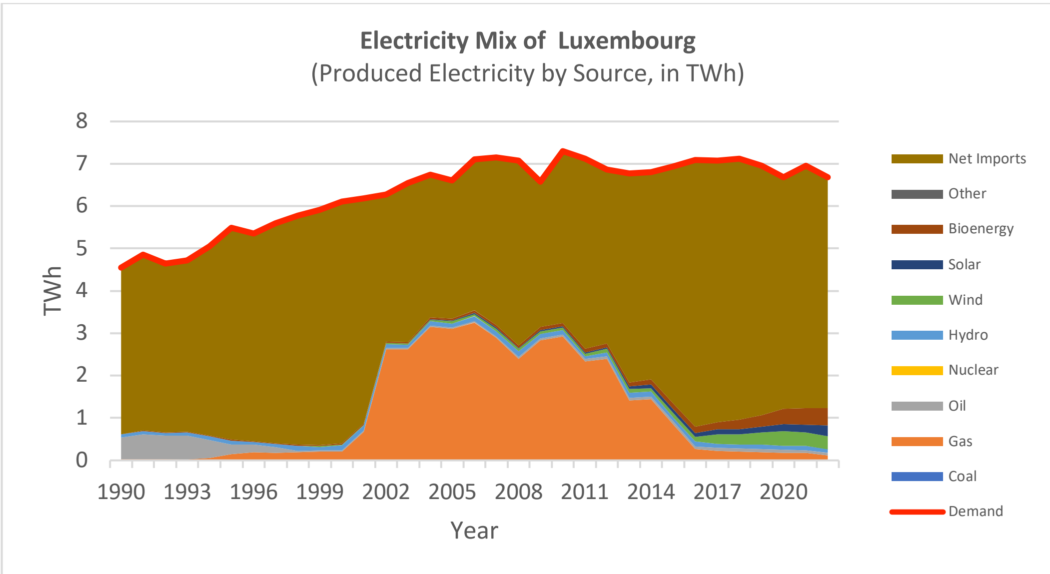

Figure 3.36: Produced electricity by source in Luxembourg since 1990. The red line indicates the electricity demand.

3.2.19 Malta

Malta is an island country of southern Europe. It consists of two main islands south of Italy in the Mediterranean Sea and covers an area of just 316 km^2. Its population reaches 520,000 inhabitants according to 2022 estimates.

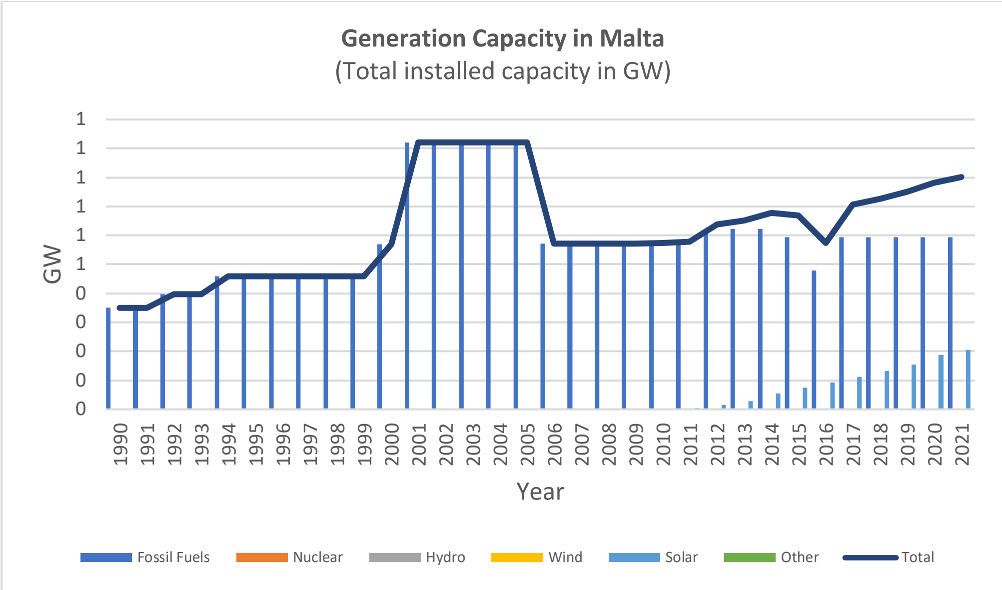

Figure 3.37: Installed capacity by source and total installed capacity in Malta since 1990.

The electricity production in Malta today is mainly based on fossil fuels. Natural gas - that is imported from other countries- is used to generate most of the electric power on the two islands as shown in **Figure 38**. The country's power plants used oil as the main source of fuel until 2015, when it was replaced by gas, keeping the first as a backup. The renewables hold a small share in the electricity mix, but their total installed capacity is increasing very fast as demonstrated in **Figure 37**. Especially solar power is gaining rapidly in popularity, due to Malta's location in southern Europe, and its high solar potential.

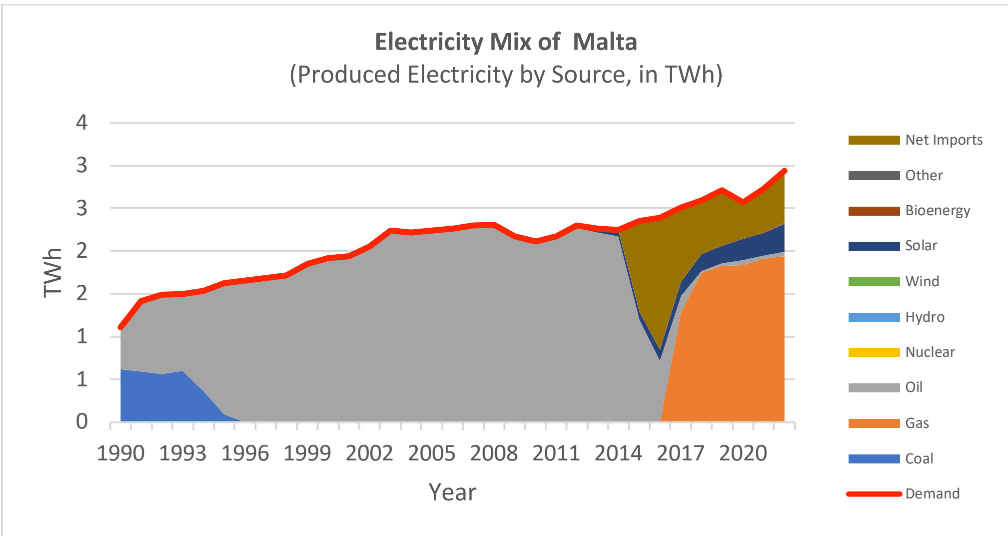

Figure 3.38: Produced electricity by source in Malta since 1990. The red line indicates the electricity demand.

Until 2014 the electricity system of the country was not connected to the European mainland grid, so Malta was not able to trade for electric power. Since the completion of its interconnection with Sicily (in Italy) in 2015, the country is capable of importing large amounts of energy when needed, which has led to a large increase of the total demand during the last decade.

3.2.20 Netherlands

The Netherlands is a country of almost 18 million inhabitants, covering an area of 42,500 km^2. Its main land body is located in northwestern Europe, although it has under its sovereignty many overseas regions and territories all around the world.

The electricity system in the Netherlands highly depends on fossil fuels. As demonstrated in **Figure 40**, the main source of electricity is natural gas, followed by coal. A small part of the energy comes from oil too. The country's nuclear reactors also contribute to the generation with a fixed percentage since the 1990s. Hydropower is almost absent from the composition of the electricity mix, while other renewables like wind and solar have significantly increased their capacity during the last 15 years. The deficit in case of large demand is covered by the interconnections of the country to its neighbors of central and western Europe.

The Netherlands currently has one of the largest shares of combustible fuels (in the electricity generation process) among all European countries. However, the national strategy aims to gradually phase out the coal operating facilities, keeping only the gas power plants on the grid. At the same time, it plans to extend the use of wind power, by constructing -mainly offshore- wind farms, taking advantage of the North Sea's great wind resources, in an effort to promote a more sustainable alternative for electric power production.

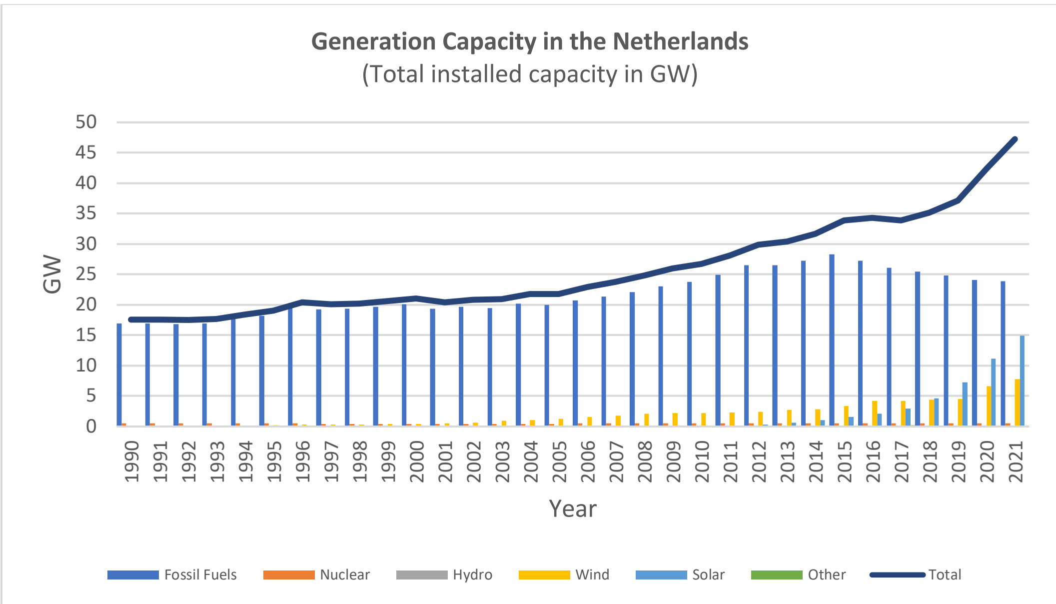

Figure 3.39: Installed capacity by source and total installed capacity in the Netherlands since 1990.

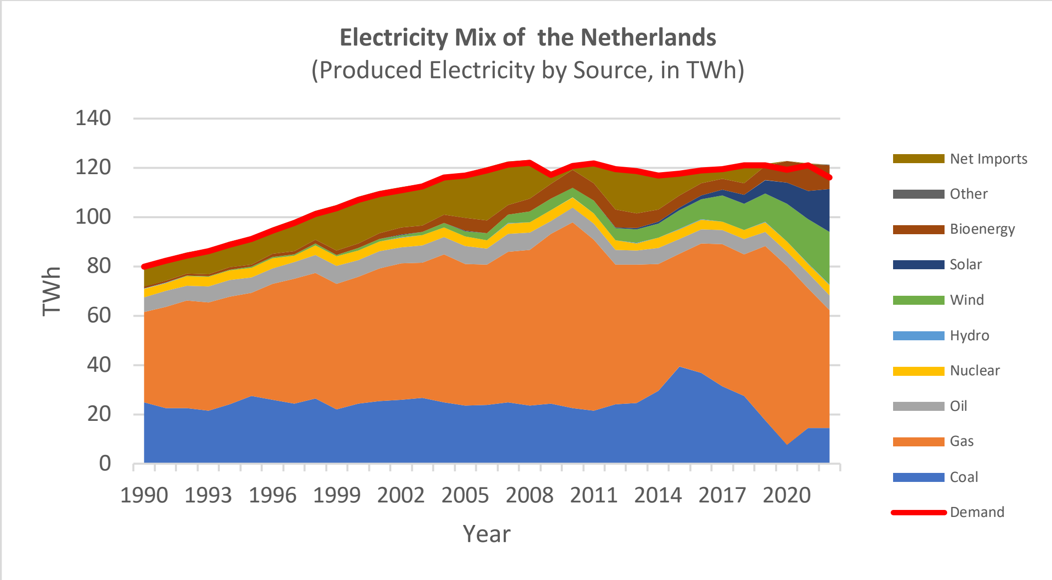

Figure 3.40: Produced electricity by source in the Netherlands since 1990. The red line indicates the electricity demand.

3.2.21 Poland

Poland is a country covering about 312,700 km^2 located in central Europe and has a population close to 37.6 million (in 2022). On the north, the country is bordered by the Baltic Sea.

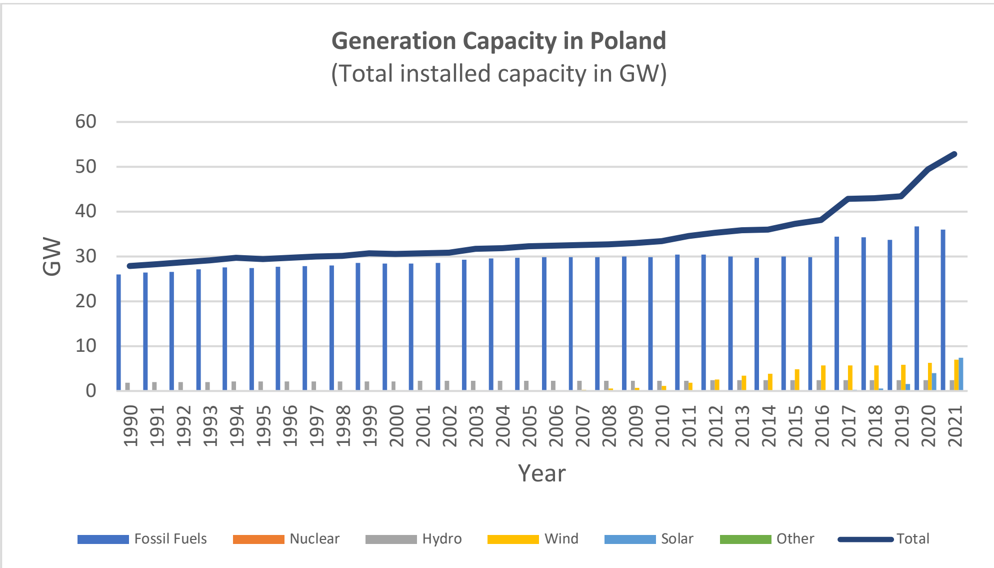

Figure 3.41: Installed capacity by source and total installed capacity in Poland since 1990.

Electricity production in Poland highly depends on fossil fuels as most of the generated power comes from thermal power plants that operate with coal. Oil and natural gas also have a share in the mix. Hydroelectric facilities exist in the country, but they are only used to balance the system during peak hours. As of 2022, there are no operational nuclear plants in the country.

The electricity sector in Poland is undergoing many changes, in recent years. Triggered by the ever-increasing demand for electricity, in the last fifteen years there have been efforts to add renewable generation capacity to the system by installing wind, solar and biofuel running facilities. Additionally, the national energy plan predicts the construction of nuclear power plants -that will start entering the system after 2030- in an effort to balance the energy security of the country.

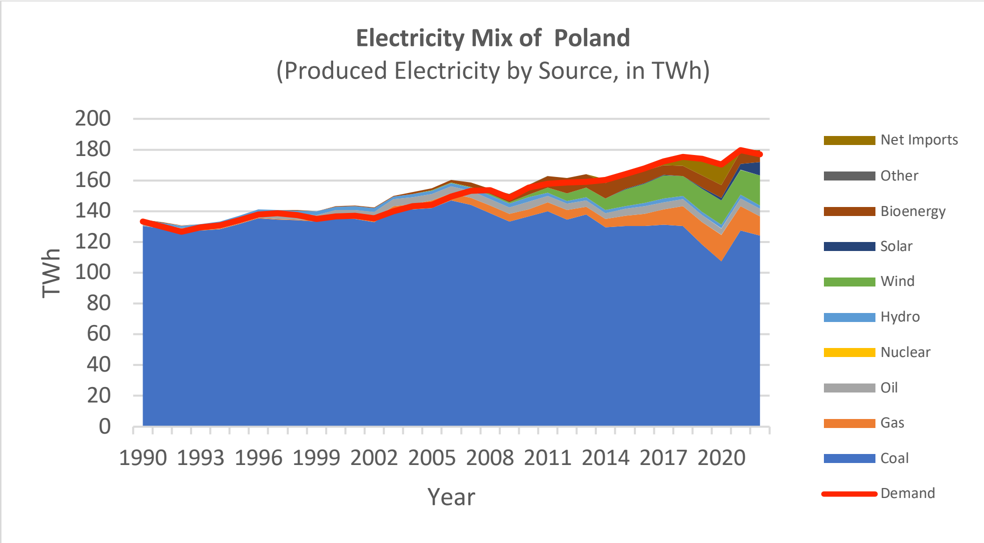

Figure 3.42: Produced electricity by source in Poland since 1990. The red line indicates the electricity demand.

3.2.22 Portugal

Portugal is a country of southwestern Europe covering an area 92,230 km^2 of and has a population of 10.4 million inhabitants according to 2022 estimates. It occupies the western part of the Iberian Peninsula, between Spain to the east and the Atlantic Ocean to the west.

The electricity in the country is produced using a wide range of primary energy sources including both combustible fuels and renewables. Conventional power plants operate in their majority by using natural gas and coal. The country's wet climate and the fact that the operating hydroelectric facilities are mainly large-scale, make hydropower the largest renewable source of energy in the country in terms of installed capacity as demonstrated in **Figure 43**. Variable renewable sources like solar and wind are also utilized to generate electricity in Portugal, and their total participation in the mix has increased significantly over the last decade as seen in **Figure 44**. The rest of the electricity needed, is imported from Spain, which is the only interconnected country to the Portuguese system.

Portugal's energy policy is aligned with the European Union's goals for low carbon emissions and aims to achieve decarbonization of the electricity production by 2050. It includes moving away from combustible fuels and investing in renewable energy projects -and especially wind and solar- to cover the demand by increasing their total generation capacity and their participation in the mix.

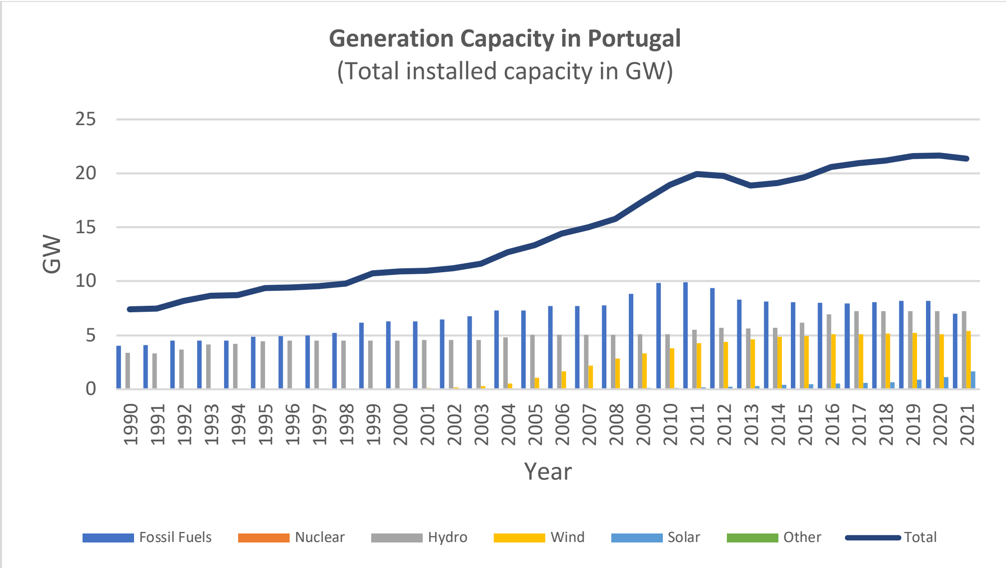

Figure 3.43: Installed capacity by source and total installed capacity in Portugal since 1990.

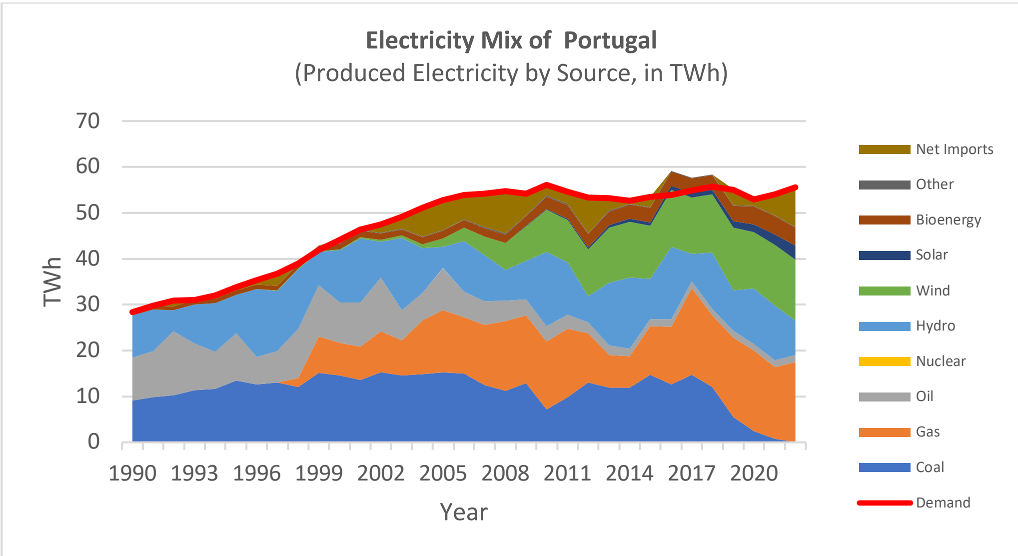

Figure 3.44: Produced electricity by source in Portugal since 1990. The red line indicates the electricity demand.

3.2.23 Romania

Located between central and eastern Europe, Romania lies in an area of almost 238,400 km^2 and has a population of 19 million (as of 2022). The Carpathian Mountains cross a large part of the country while the Black Sea borders it to the east.

Romania has a diverse energy mix that includes coal, natural gas, nuclear, hydroelectric, and other renewable sources. Historically, the largest part of electricity was produced by fossil fuels -and mainly coal- and it was followed by hydroelectric and nuclear power that contributed with electricity produced by the country's only nuclear power station (ITA, 2024). Lately, the share of variables (including both wind and solar) has increased significantly.

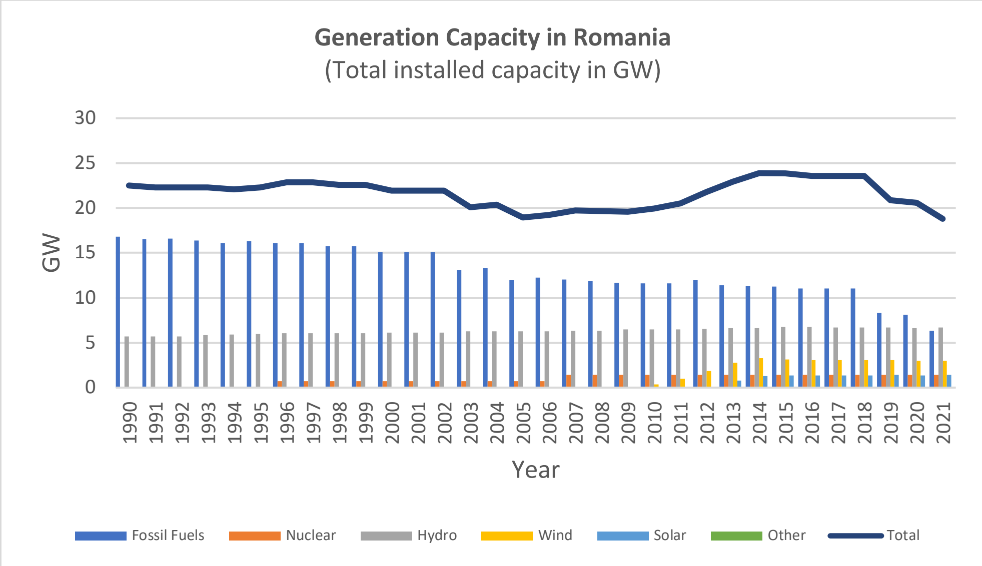

Figure 3.45: Installed capacity by source and total installed capacity in Romania since 1990.

The national plans to gradually decommission the country's coal power plants, has led to the introduction of more renewable sources to the mix and at the same time the government intends to increase the nuclear generation capacity by the construction of new nuclear plants in the near future.

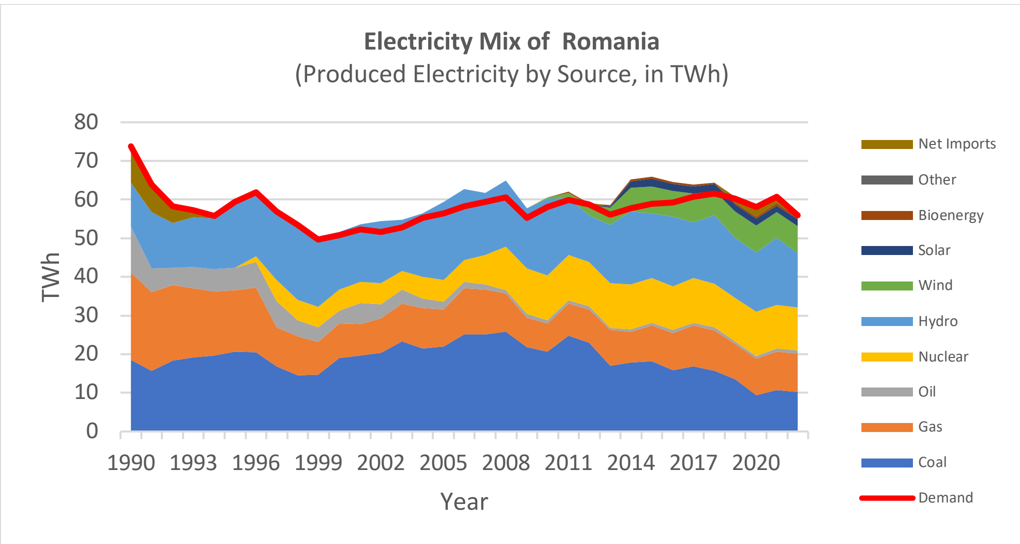

Figure 3.46: Produced electricity by source in Romania since 1990. The red line indicates the electricity demand.

3.2.24 Slovakia

Slovakia is a country of central Europe, covering an area of little over 49,000 km^2 and has a population of around 5.4 million according to 2022 estimates.

The electricity sector in Slovakia is characterized by the dominance of nuclear power, as its plants generate almost 60% of the total domestic production, making it one of the European countries with the largest share of nuclear power in their mix. Hydroelectric power is the second largest source at a national level, while other renewables and a small proportion of fossil fuels -the use of which has decreased significantly over the last years- complete the mix. The total generation usually surpasses the demand making the country a net importer in the region.

Slovakia's energy sector is currently undergoing interesting changes as it upgrades its electricity system and expands the interconnections with the neighboring countries of the central European area. At the same time, the country is planning to increase its nuclear generation capacity by constructing new units, targeting in a more secure supply system and a potential ability to become a net electricity exporter in the future.

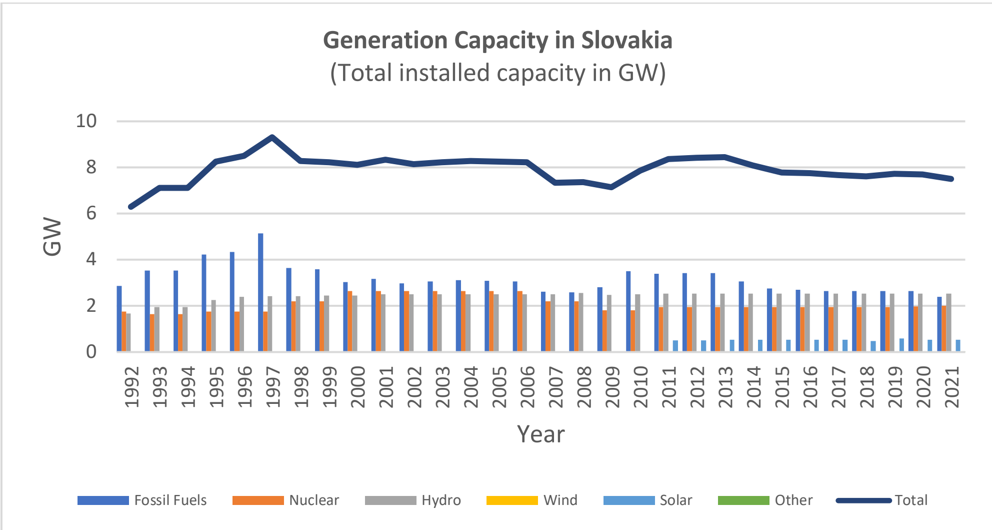

Figure 3.47: Installed capacity by source and total installed capacity in Slovakia since 1992.

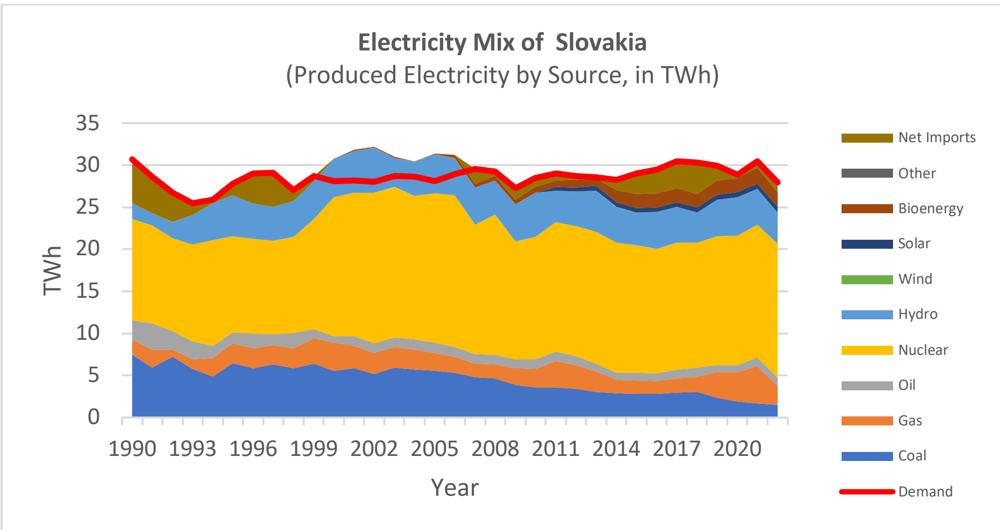

Figure 3.48: Produced electricity by source in Slovakia since 1990. The red line indicates the electricity demand.

3.2.25 Slovenia

Slovenia is a country of around 20,270 km^2 in the southern part of central Europe, next to the coasts of the Adriatic Sea. It is surrounded by Austria, Croatia, Hungary and Italy and it has an estimated population of 2.1 million as of 2022.

Its energy supply highly depends on three main sources, coal and nuclear and hydroelectric power. The three combined generate almost all the domestic electricity. Small power quantities of are also produced from the few renewable facilities in the country. As demonstrated in **Figure 49**, Slovenia's generation capacity has shown a notable increase since the early 1990s and the total electricity production usually exceeds the demand as seen in **Figure 50**. Hence, Slovenia it is an electricity exporter in the region trading electric power mainly with the nearby markets of central Europe.

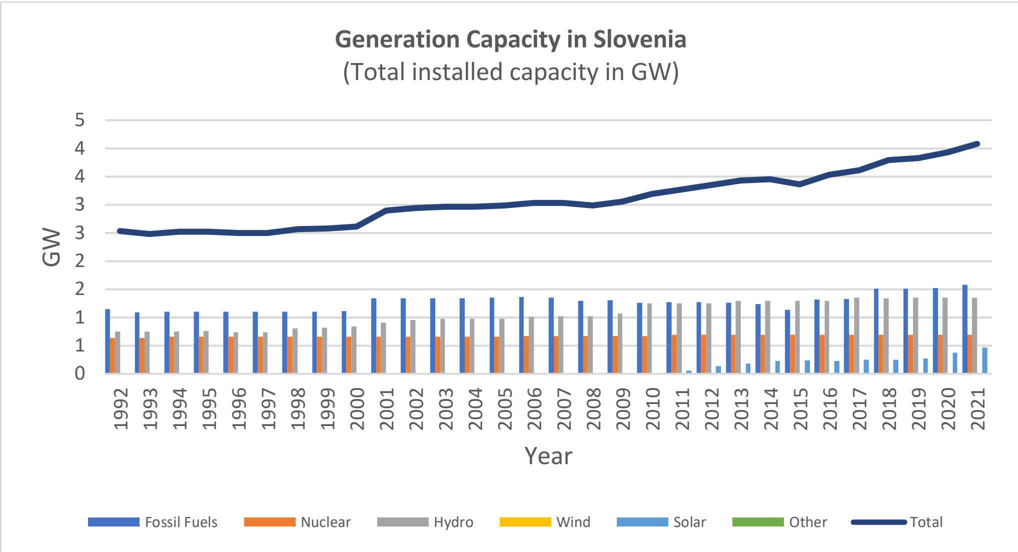

Figure 3.49: Installed capacity by source and total installed capacity in Slovenia since 1992.

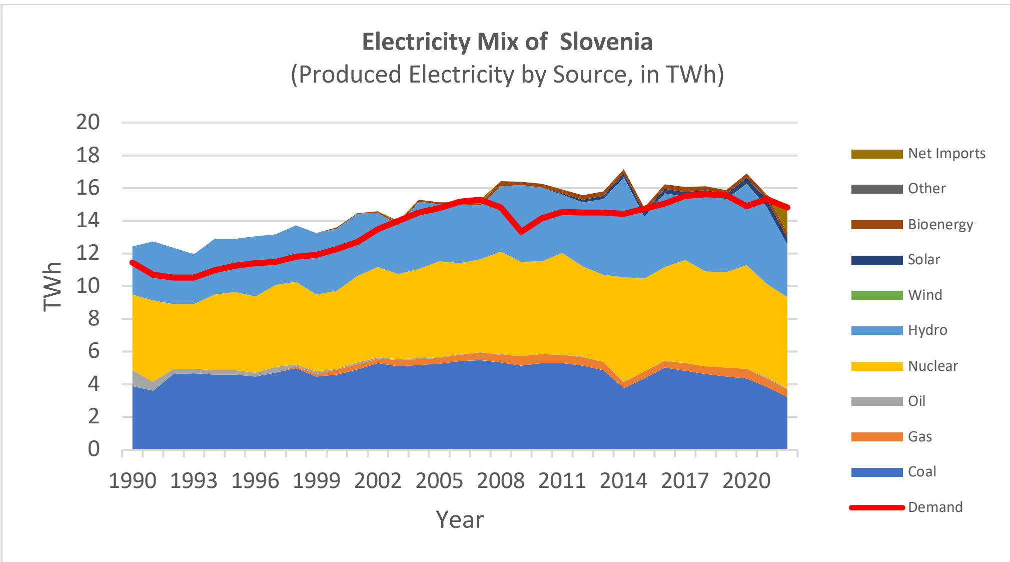

Figure 3.50: Produced electricity by source in Slovenia since 1990. The red line indicates the electricity demand.

3.2.26 Spain

Spain is located in southwestern Europe covering an area of 505,990 km^2 and has a population of 47.6 million inhabitants as of 2022, making it one of the most populous countries of the European Union. It occupies the largest part of the Iberian Peninsula, and it is bordered by Portugal to the west and France and Andorra to the northeast.

The electricity in the country is produced using a wide range of primary energy sources including combustible fuels, renewables, and nuclear power. The used conventional sources are oil, coal and natural gas, though their participation in the mix has shown a significant decline over the past years, as they are gradually replaced by renewables. Wind power capacity increases rapidly on an annual basis, while the country's high solar potential favors the quick growth of solar power investments. Lastly, hydropower has contributed to the mix in fixed quantities since the 1990s.

In the last decade, the decarbonization of electricity generation in Spain has been visible with the dynamic introduction of renewables to the system. The energy policy followed by the government, includes the gradual decommission of all the domestic nuclear plants by 2027. It also predicts phasing out all the coal powered facilities in the near future and producing at least three quarters of the total electricity by renewables until 2030, in an effort to make a transition to more clean sources of energy.

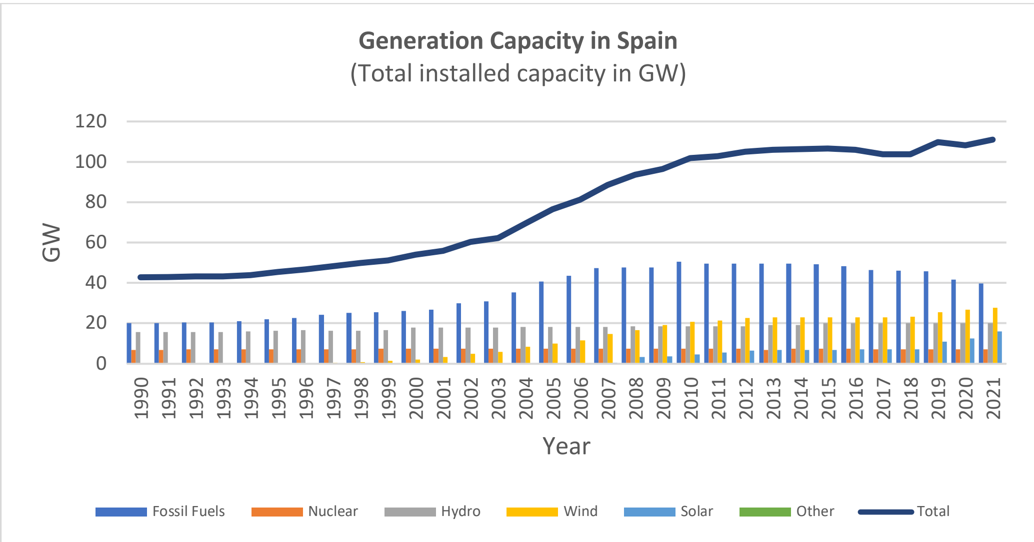

Figure 3.51: Installed capacity by source and total installed capacity in Spain since 1990.

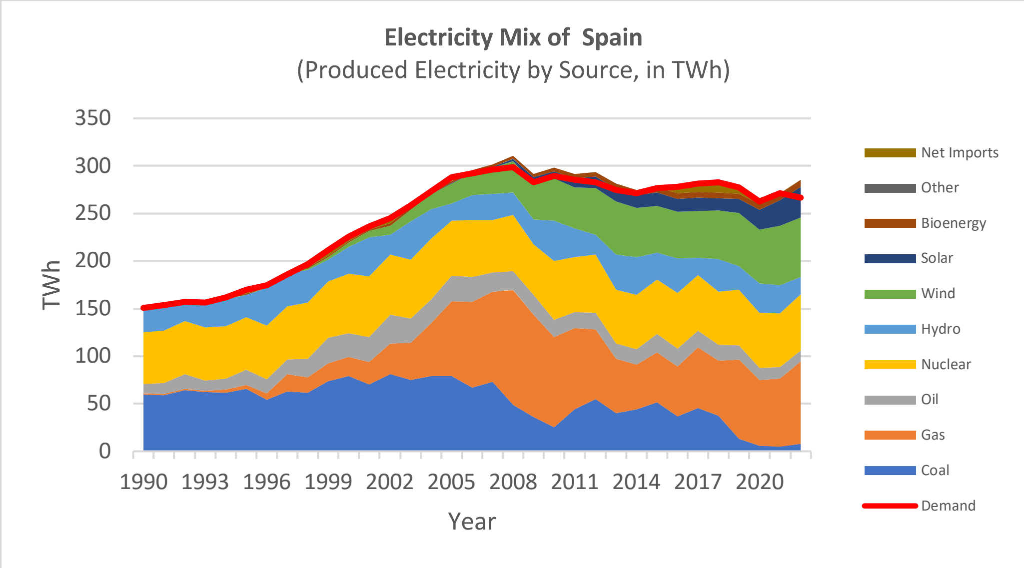

Figure 3.52: Produced electricity by source in Spain since 1990. The red line indicates the electricity demand.

3.2.27 Sweden

Sweden is a Nordic country of northern Europe, occupying the east part of the Scandinavian Peninsula and covers an area of almost 450,300 km^2. It has 10.5 million inhabitants based on 2022 estimates.

The two main sources of energy in the country are nuclear and hydroelectric power, which together produce almost all the electricity of Sweden. More specifically, hydropower is used on such a large scale because Sweden has one of the richest water supplies in Europe, owing to its mountainous landscape and its geographical position in the northern part of the continent. Fossil fuels are almost absent from the composition of the country’s electricity mix, while renewable sources and especially wind power have gained in popularity since the early 2010s.

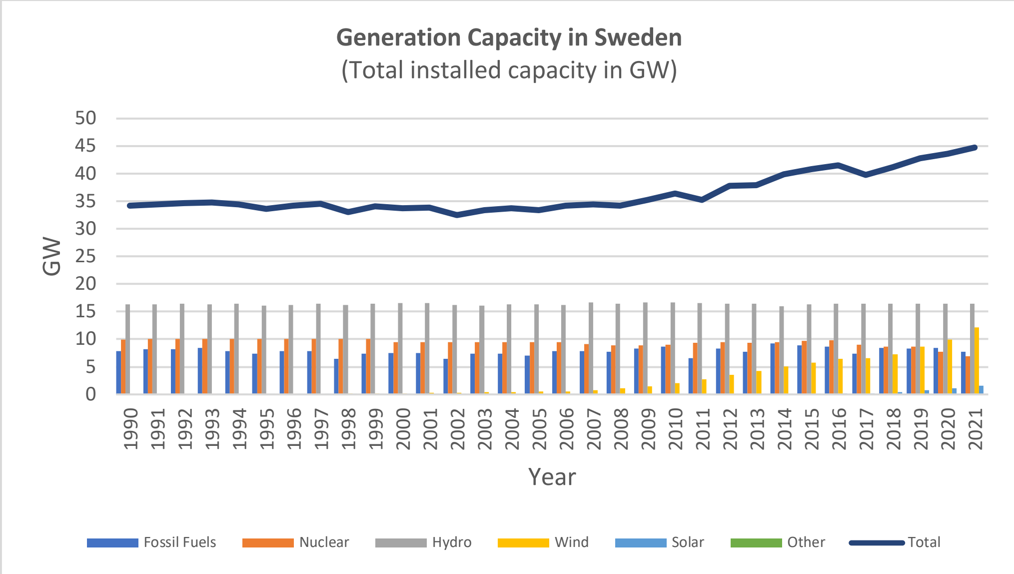

Figure 3.53: Installed capacity by source and total installed capacity in Sweden since 1990.

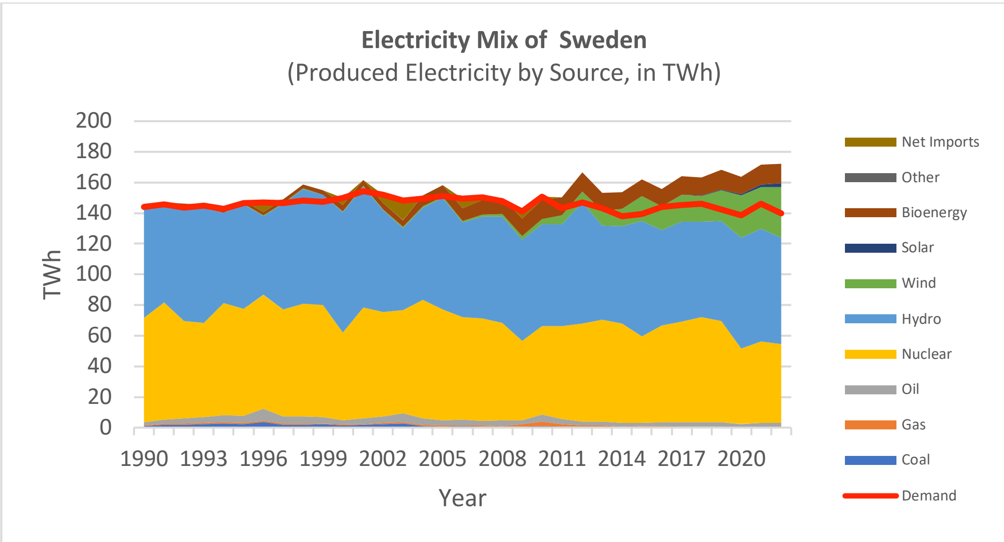

Figure 3.54: Produced electricity by source in Sweden since 1990. The red line indicates the electricity demand.

Sweden is generally exporting the surplus of its production to the neighboring Nordic countries. Its electricity system is characterized by high reliance on nuclear power and renewable sources, with hydropower on the lead and wind power continuously increasing and has achieved to be resilient and adaptive to the constantly changing circumstances.

3.2.28 Iceland

Iceland is an island country that lies between Europe and North America in the North Atlantic Ocean. It covers an area of 103,125 km^2 and its population reaches 380,000 inhabitants according to 2022 estimates.

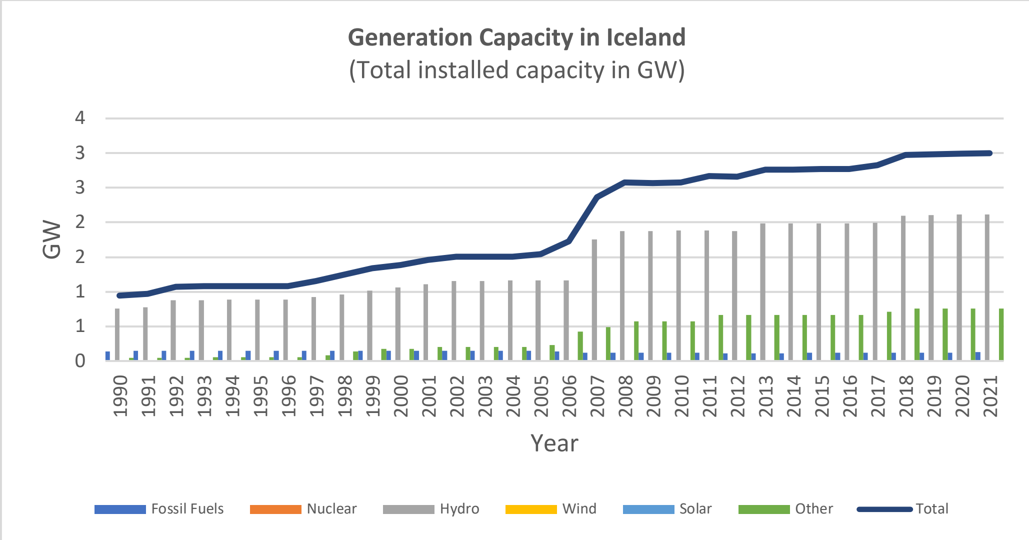

Figure 3.55: Installed capacity by source and total installed capacity in Iceland since 1990.

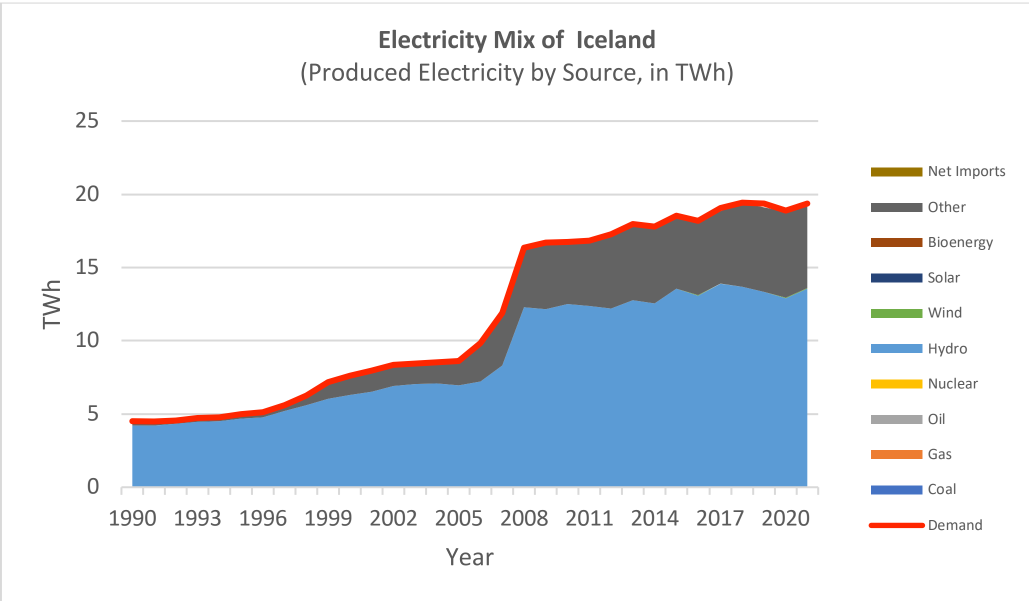

Figure 3.56: Produced electricity by source in Iceland since 1990. The red line indicates the electricity demand.

Almost all the electricity production in the country comes from renewable sources with hydropower and geothermal energy composing almost 100% of the generation mix, as seen in **Figure 56**. The abundance of water and thermal energy from the ground is based on the favorable geography and geological conditions of Iceland and for this reason it is used on such a large scale. In terms of generation capacity, the system includes some fossil fuel facilities (**Figure 55**), which only operate to balance the demand during peak hours.

The country due to its geographic isolation and its long distance from mainland Europe, is currently not interconnected to other countries' systems. Therefore, the potential challenges for its electricity system include maintaining self-efficiency and covering the electricity demand in long term timescales.

3.2.29 Norway

Norway is a country in northern Europe, occupying the western part of the Scandinavian Peninsula. It covers an area of about 385,200 km^2 and borders Finland, Russia and Sweden. It has 5.5 million inhabitants based on 2022 estimates.

Norway's generated electricity comes almost exclusively from renewable sources. Hydropower has historically been the most used source for electricity production, sharing more than 90% of the total generation mix annually. The reason of such an extensive use of hydropower is the country's mountainous landscape -forming many valleys crossed by rivers- combined with the high levels of precipitation Norway receives. The second largest source is currently wind power, both in terms of installed capacity and in terms of electricity generation, having considerably increased its total participation to the mix during the last decade. The system also includes a few solar power installations and some natural gas-powered plants, while nuclear power is not used in the country.

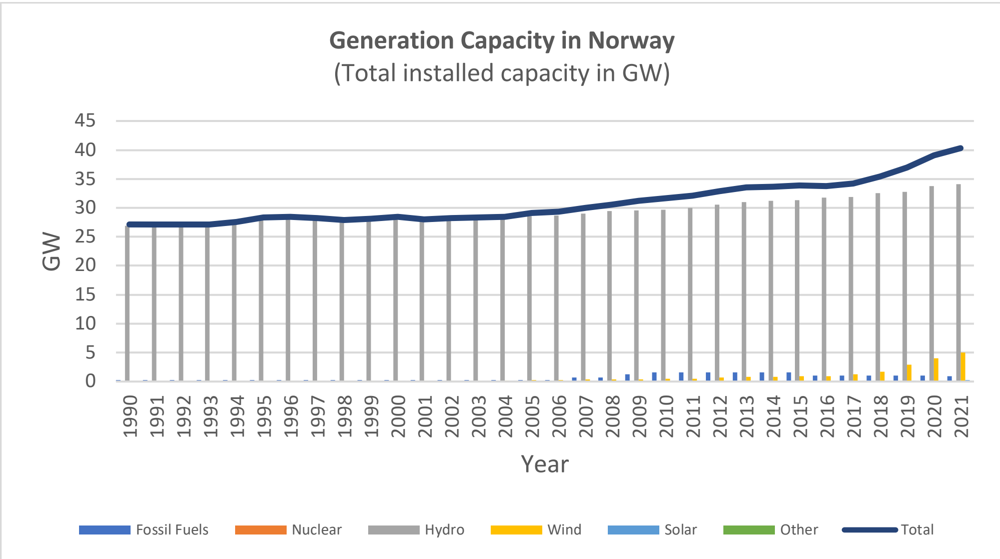

Figure 3.57: Installed capacity by source and total installed capacity in Norway since 1990.

Today, Norway is a leader in the use of renewable energy, and successfully manages to ensure its electricity supply and cover the needs of its industry and households. It has a modern transmission system and good interconnections with the neighboring countries, allowing the trade of its surplus principally in the Nordic market.

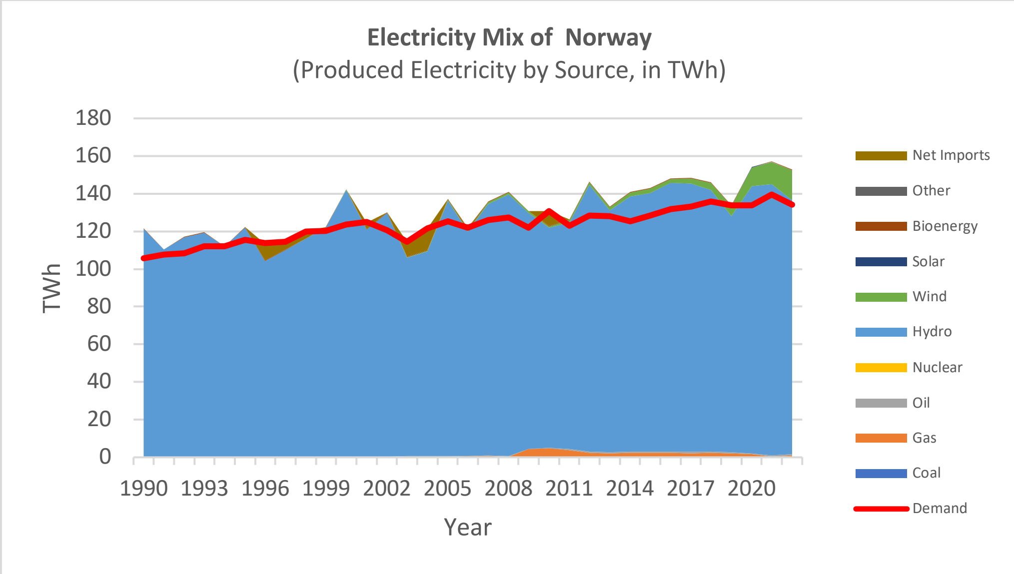

Figure 3.58: Produced electricity by source in Norway since 1990. The red line indicates the electricity demand.

3.2.30 United Kingdom

The United Kingdom is an island country located in northwestern Europe. It consists of the island of Great Britain and the north part of Ireland (bordering the Republic of Ireland to the south) and it has under its sovereignty many overseas regions and territories all around the world. The total area of the country is about 244,400 km^2 and its population exceeds 67 million based on 2022 estimates.

United Kingdom's large electricity sector needs to ensure sufficient supply to the country's households and mainly to its heavy industry. The electricity in the country is produced using a wide range of primary energy sources including combustible fuels, renewables, and nuclear power. Until the late 2010s, the major source of electricity was coal, generating more than a third of the total production followed by other combustibles and nuclear, though currently natural gas is the most used conventional source. The renewables, include hydropower, solar, wind and bioenergy; especially wind power continuously gains ground the last 15 years, taking advantage of Britain's high wind potential and increasing significantly its participation in the mix as demonstrated in **Figure 60**.

As we can see in **Figure 59**, the total generation capacity of the system continuously increases even though the demand for electricity has shown a considerable decrease since the mid 2000s. The energy policy of the country includes gradually substituting conventional power plants with renewable energy facilities and trying to make a transition to more clean sources of electricity.

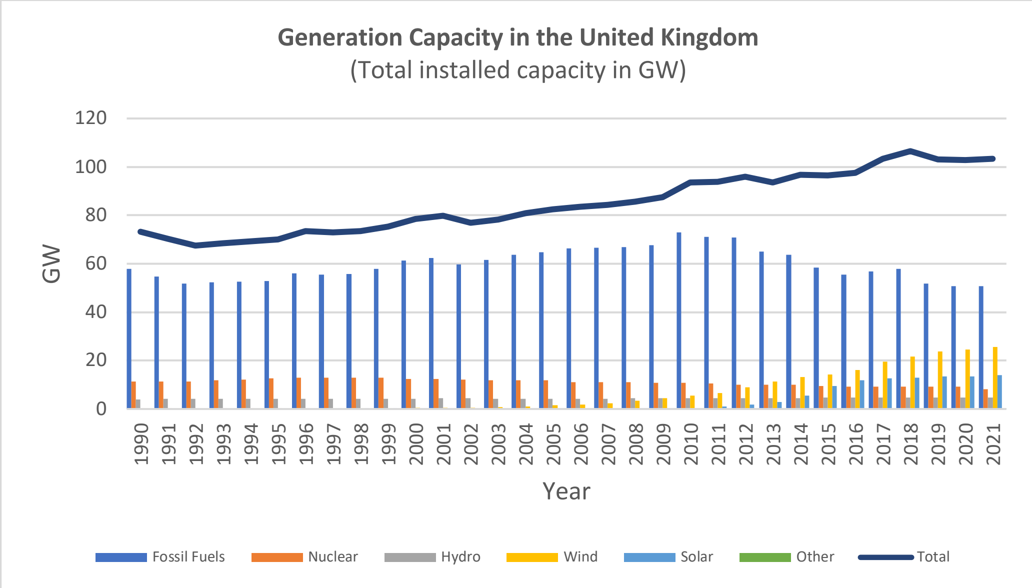

Figure 3.59: Installed capacity by source and total installed capacity in the United Kingdom since 1990.

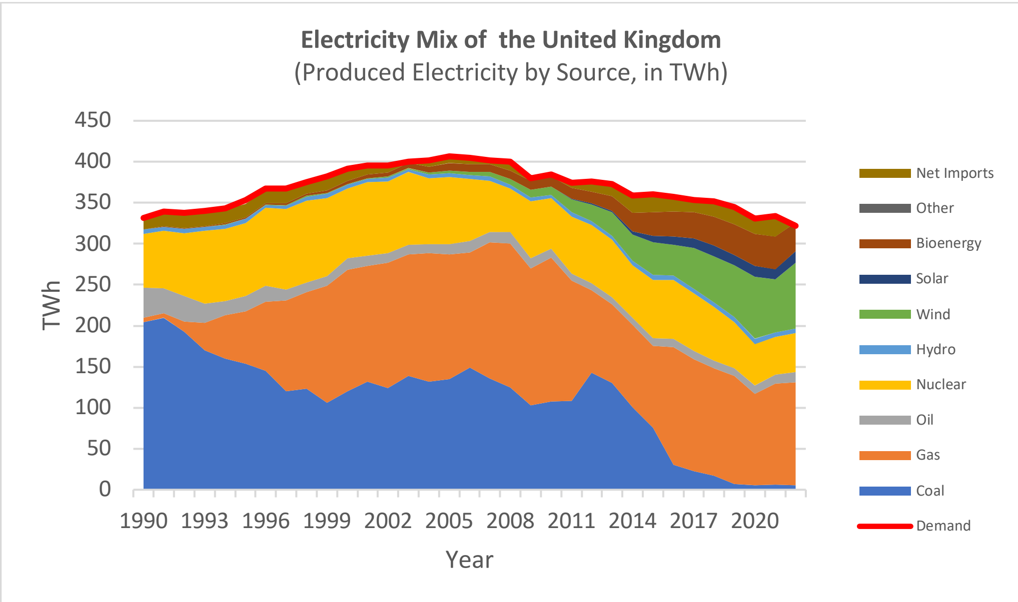

Figure 3.60: Produced electricity by source in the United Kingdom since 1990. The red line indicates the electricity demand.

Chapter 4: Integration of renewables in European grids

4.1 Introduction

Hydropower is a renewable source that has been used in the energy sector for electricity production for a long time. However, the popularity of renewable energy began to surge rapidly with the introduction of variable sources, mainly wind and solar power. Today, the use of renewable sources for electricity generation plays a decisive role in shaping the energy policy of a country. Considering their contribution to the mitigation of the consequences of climate change to the environment (principally their clean origin and their little to zero greenhouse emissions), many countries adopt them and gradually compose an energy profile based on them rather than on conventional sources. In the larger part of the European continent, the electricity supply -that for most of its history depended on fossil fuels- is rapidly moving towards renewable sources. The European Union has already set a long-term target to increase the share of electricity generated from renewable sources to an 80% by 2050 (IEA, 2020), and the countries that were examined in the previous chapter follow more or less similar policies.

In this chapter, are highlighted the changes across renewable energy sources, in terms of electricity generation and total installed capacity over a period of 30 years. We also note down the geopolitical factors that may have affected those changes. The data used, range from 1992 to 2021 covering a full three-decade period and refer to the countries that were already examined in chapter 3. The recording is done for each renewable source separately including hydro, wind and solar and the last sub-chapter is dedicated to the renewables as a whole.

4.2 Hydropower

Hydropower has played a key role in the energy sector of most European countries, as until now it has been the most used renewable source for electricity generation producing 511 TWh in the studied countries in 2021 alone. Considering the variable nature of the other renewables (wind and solar), the presence of hydropower in the electric system is vital, since the large hydroelectric plants have the ability to store water in reservoirs and supply the grid with electricity within minutes. In this respect, they are able to cover the total demands and balance the grid during the peak consumption periods.

The amount of electricity produced from hydropower highly varies between the European countries as seen in **Figure 4.1**. Norway, Iceland and Austria have the highest participation of hydro to their electricity mix, mainly due to their mountainous relief that allows them to construct large dams in steep valleys and take advantage of the high water potential, while island countries like Cyprus and Malta produce zero hydroelectricity as their small size and limited water resources (rivers) makes hydropower unsuitable for the cover of their electricity demand.

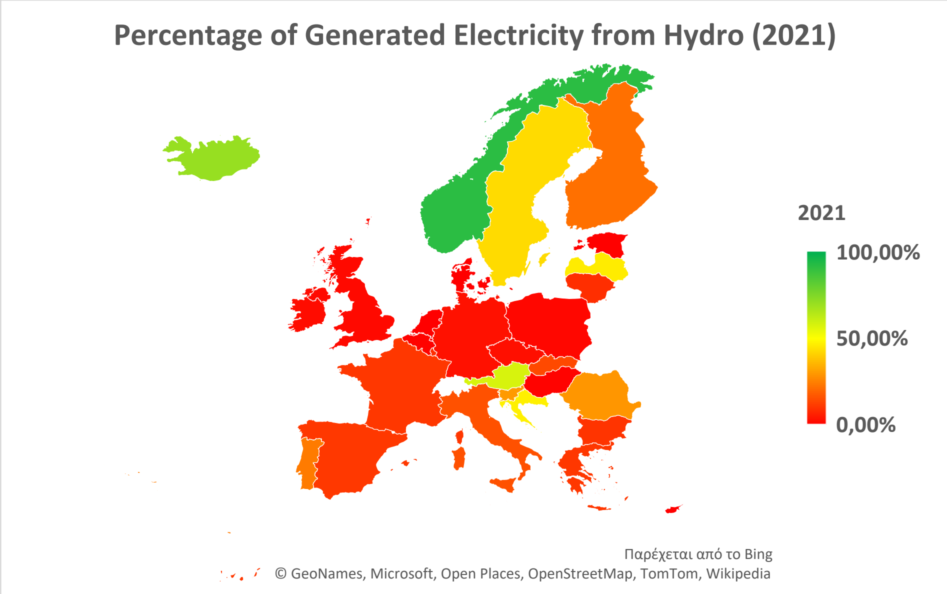

Figure 4.1: Percentage of Generated Electricity from Hydro in Europe (2021).

In terms of generation capacity, Norway comes first counting almost 35 GW in 2021, followed by France, Italy, Spain and Sweden, while the island countries mentioned above have no hydroelectric installations (**Figure 4.2**). The total capacity of hydroelectric power plants has shown a steady growth since the early 1990s and as of 2021 it has exceeded 190 GW in the studied countries, as demonstrated in **Figure 4.3**.

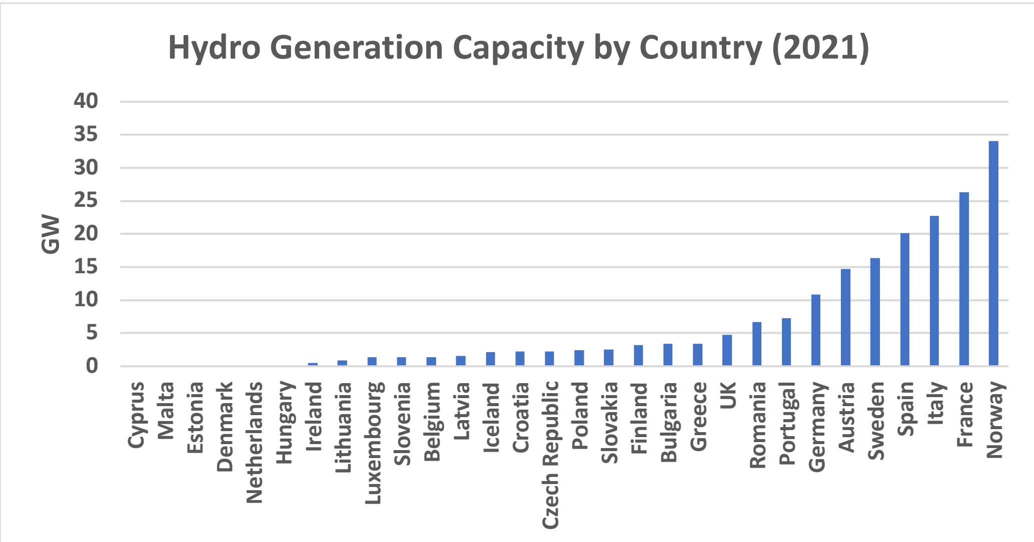

Figure 4.2: Hydro Generation Capacity by Country (2021).

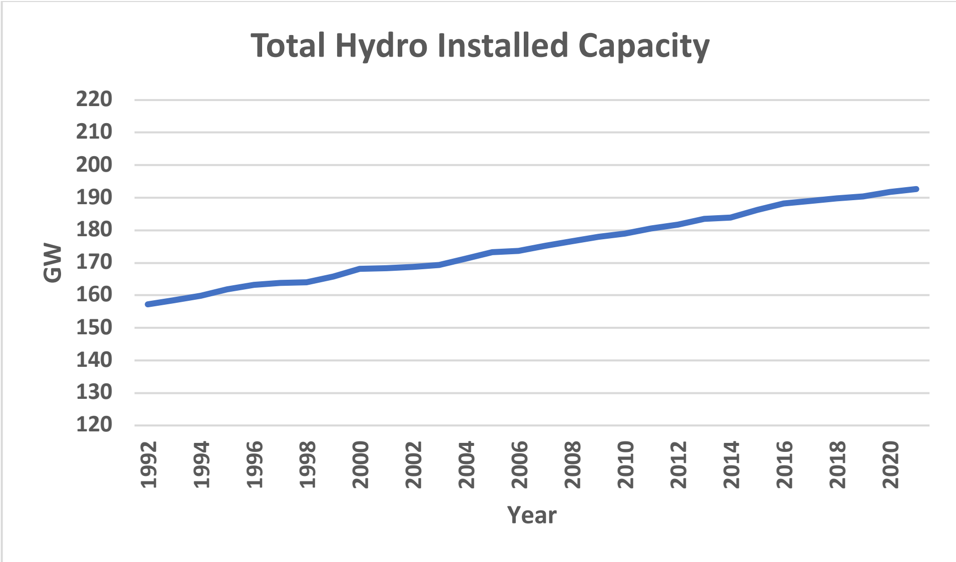

Figure 4.3: Change in the total Hydro Generation Capacity of EU-27 plus Iceland, Norway and the UK.

As we can see, installed capacity does not have an annual variation, in contrast to the electricity generated each year from the hydroelectric facilities. This mainly occurs due to climate and hydrological conditions like the temperature and the total precipitation a region receives during a specific time period. Those factors highly affect the quantity of water and thus the operation of the power plants both at seasonal and in annual level. For instance, snow melting leads to higher flow rates during the late spring and summer, creating a periodical increase in the availability from the perspective of one year's period; on the other hand, large droughts affect the largest timescales like a few years (Gøtske & Victoria, 2021). Other factors affecting electricity generation include the way a country operates its hydroelectric plants -as base or peak electricity infrastructure- and of course the level of contribution of the other electricity sources to the mix.

Although the installed capacity of the hydroelectric power plants continuously increases since 1992, hydropower's percentage in the total generation capacity presents a small decline in the 30-year period we study. **Figure 4.4** shows that with a few exceptions, most of the European countries -including those who have large integration of hydro- have reduced their percentages with the biggest decrease being visible after 2010. The main reason, for this is the rapid accession of variable renewables (solar and wind); the quick pace of construction of those power facilities has increased remarkably the total capacity, leaving a smaller share to hydro. Exceptions include countries like Slovakia, Slovenia and countries of eastern Europe like Bulgaria or Romania, which have not yet invested extensively to other renewables than hydro. The case of Lithuania is of great interest, as despite increasing its solar and wind capacity, the decommissioning of its nuclear plants, has helped hydro increase its percentage to the total capacity of the country.

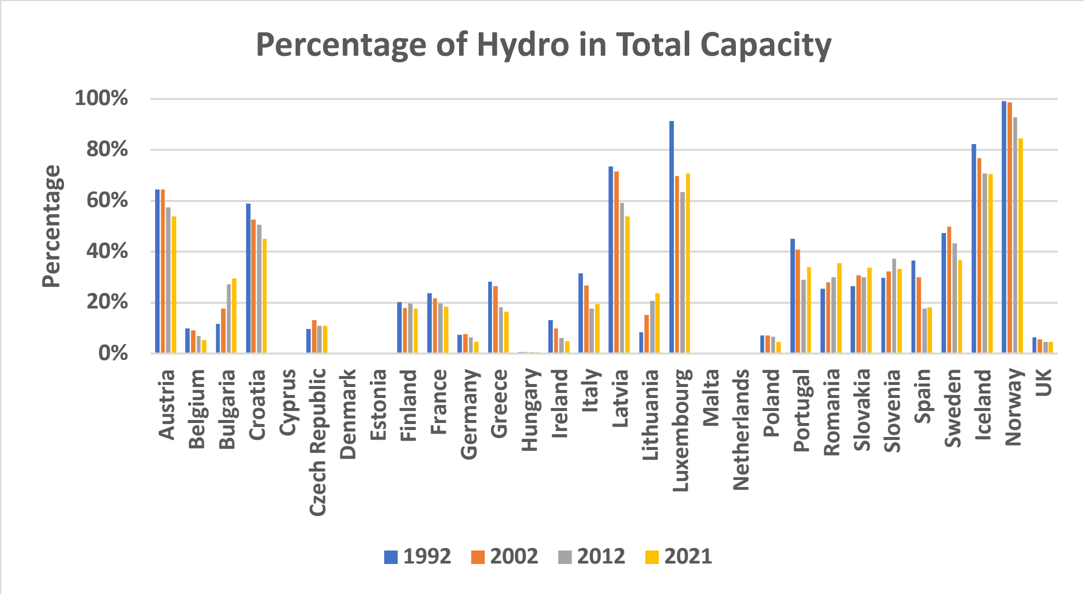

Figure 4.4: Change of hydro as part of the total generation capacity.

The same conclusions arise from the following figure that demonstrates the percentage difference in electricity production from hydropower facilities across Europe from 1992 to 2021 (**Figure 4.5**). The map shows that most of the countries have reduced the participation of hydro to the mix by covering the demand with other renewable sources. A typical example is that of Iceland, which indicates a fall in the contribution of hydro mainly due to the introduction of geothermal power stations to the country; and although the total amount of hydroelectricity produced in Iceland has more than doubled, the increase in demand and in geothermal generation have dropped the percentage of hydro to the mix from an almost 95% in 1992 to 70% in 2021 marking a fall of 24 percentage units. The countries of central Europe have maintained the participation to more or less the same levels, while the countries of eastern Europe have slightly increased the share of hydropower in their mix.

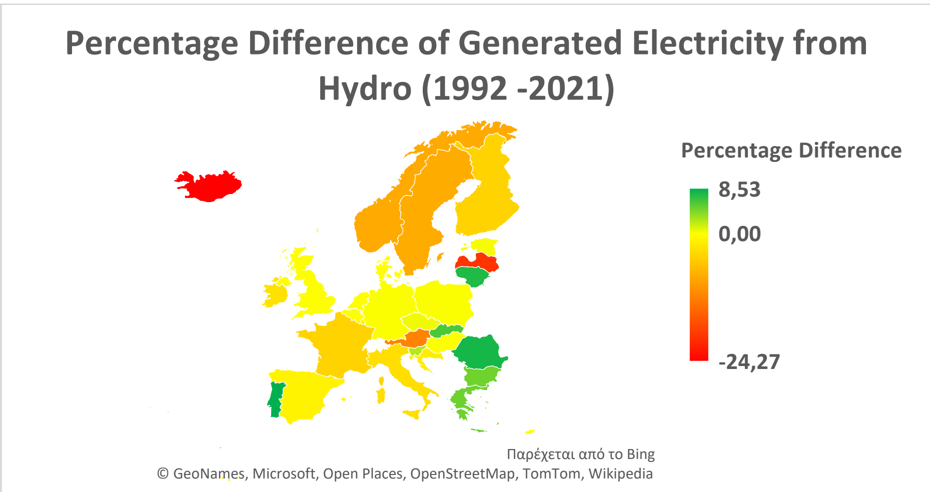

Figure 4.5: Percentage Difference of Generated Electricity from Hydro.

Finally, it is worth mentioning that despite the reduction of the share of hydropower in most countries' electricity mix, its total installed capacity continues to grow as it serves as a safety net and secures each electric system -mostly because of its ability to store power and use it when needed- against the risk deficit in the electricity supply.

4.3 Wind

Wind power has undergone an impressive transformation in Europe the recent years and it is becoming a very critical component of the continent's energy strategy. Currently it is the largest renewable -excluding hydro- source of electricity in Europe, producing annually more than 460 TWh (2021 record). Taking into consideration the total generation capacity of all the operating wind farms across the studied countries, wind power has even left hydro behind, marking a total of 219 GW installed in 2021.

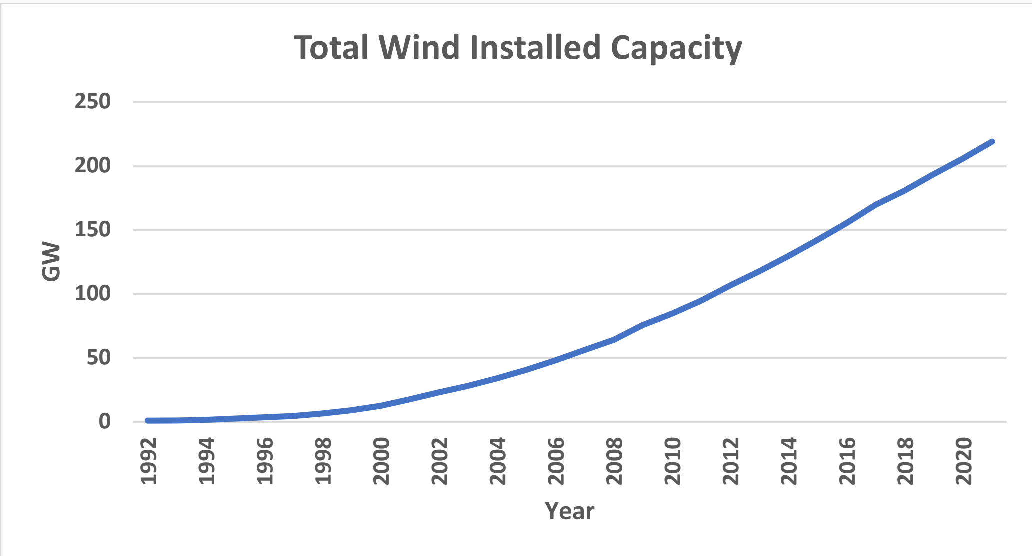

Figure 4.6: Change in the total Wind Generation Capacity of EU-27 plus Iceland, Norway and the UK.

The wind capacity has shown an exponential increase since the mid-1990s as demonstrated in **Figure 4.6**, mainly due to the necessity of integration into the European grids of low-carbon electricity, in order to achieve the decarbonization targets. **Figure 4.7** shows the generation capacity by country, indicating that as of 2021 Germany has by far the most in absolute numbers, exceeding 60 GW and more than double than of Spain, which comes second to the list.

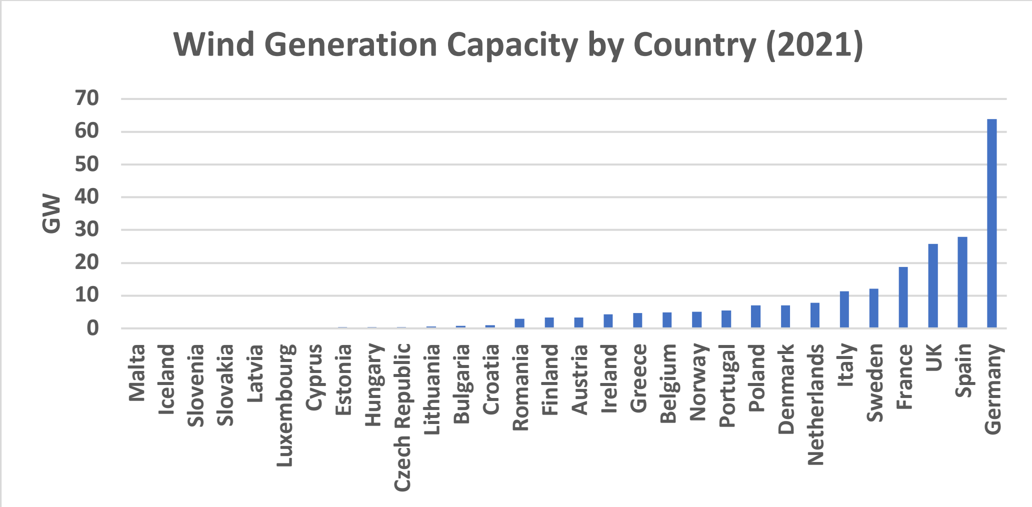

Figure 4.7: Wind Generation Capacity by Country (2021).

Along with the total capacity, the share of wind power to the composition of each nation's electricity capacity continuously increases, with no exceptions, and as of 2021, many countries have a percentage of wind capacity over 20%. Denmark and Ireland currently have the largest share of wind installations integrated into their electric systems with 42% and almost 39% respectively. **Figure 4.8** indicates that the major growth of wind power took place in the 2000s with a considerable increase in the following decades, except for Denmark, which started developing both offshore and onshore wind power projects as early as 1970; taking advantage of its location between North and Baltic Sea and the area's high wind potential, the country has achieved the highest percentages of wind participation between all electricity systems across Europe.

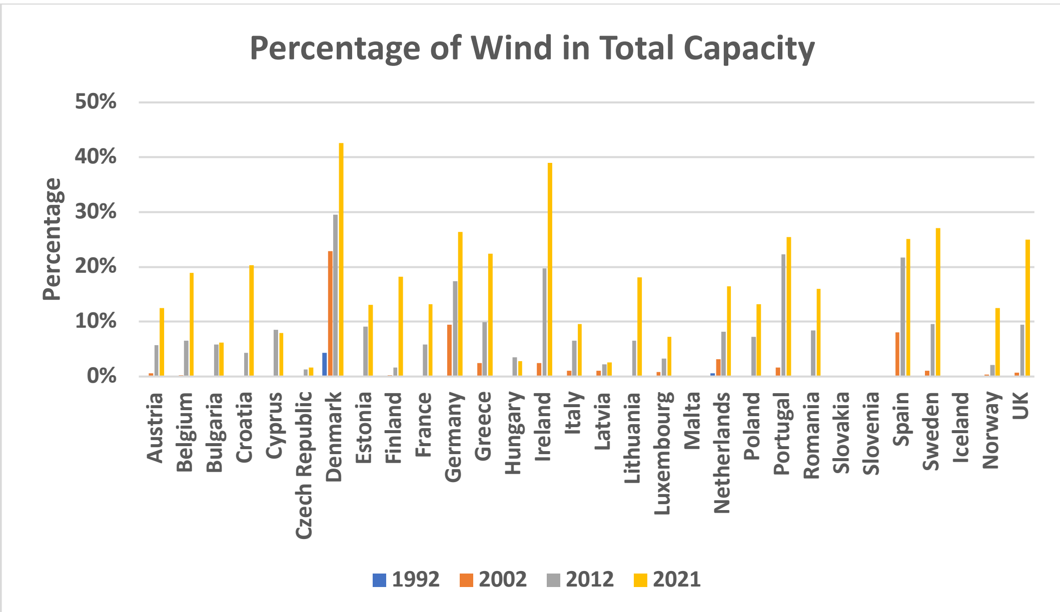

Figure 4.8: Change of wind as part of the total generation capacity.

The amount of electricity produced from wind farms, and the contribution of wind power to the generation mix also varies from country to country, but overall, they both have been ceaselessly increasing since 1992. The main reasons include technological improvements that have been made both on the turbines size and efficiency. This allows for largest and more efficient wind turbines with the capability of producing more electricity compared to the past. The new technologies have also led to important cost reductions and have increased the countries' investments in this type of renewable energy. **Figures 4.9** and **4.10** present the percentage of generated electricity coming from wind in 1992 and 2021 respectively. It is clear that all the countries have increased the share of wind power in their mix, and most of them at remarkable levels; the majority had almost 0% contribution of wind power in 1992 and managed to reach the level of producing one third of their total electricity from wind in less than 30 years with Ireland and Lithuania being such examples. Finally, Denmark (as of 2021) has managed to produce almost half of its electric power from wind farms, ensuring the country's leading position in wind power at a global level.

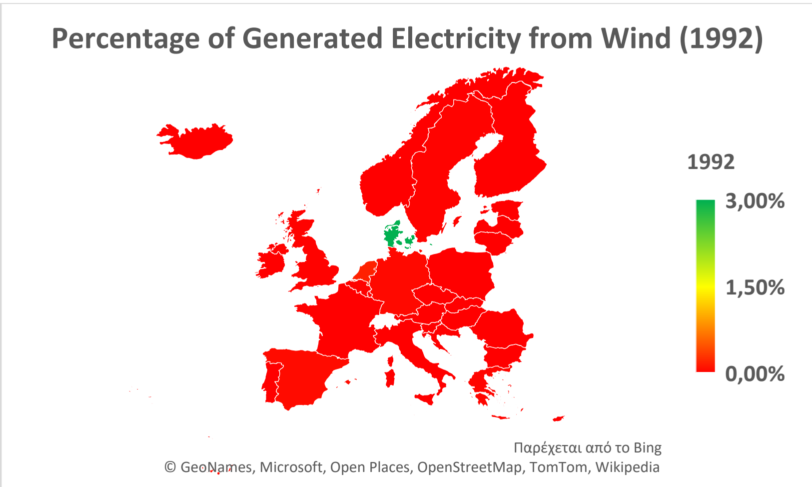

Figure 4.9: Percentage of Generated Electricity from Wind in Europe (1992).

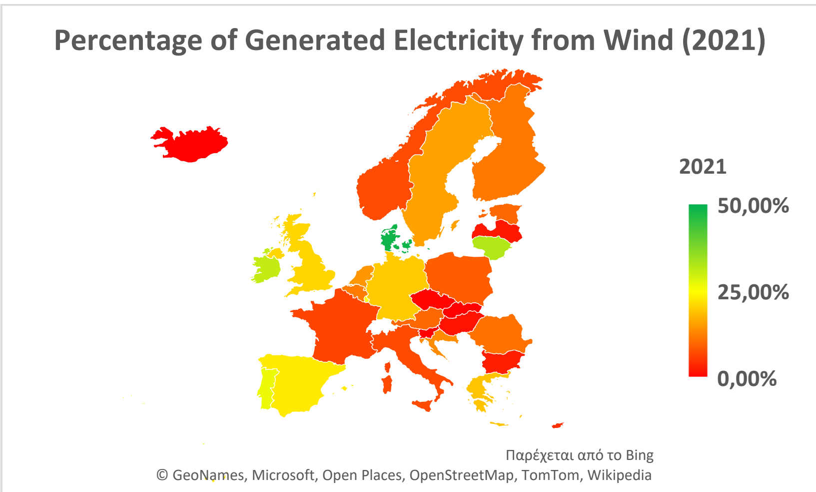

Figure 4.10: Percentage of Generated Electricity from Wind in Europe (2021).

4.4 Solar

Along with wind power, solar power has experienced an impressive penetration throughout the years. Currently it is one of the fastest growing energy sources in Europe and its evolution is an output of the technological advancements and the changes in energy policies of each country. As of 2021, its total generation capacity had reached 180 GW, while at the same time 176 TWh of electricity were produced in the countries we investigate.

Solar power is a relatively new way of generating electricity and began to appear on a very low basis in 1990. Its initial growth phase included pilot and research projects and until the mid-2000s the total solar capacity in Europe did not exceed 1 GW. From then on, the improvements in technology allowed the construction of more efficient and cheaper panels that produced more electricity. Therefore the next decade (up to mid-2010s) solar power experienced an explosive growth, managing to increase its capacity one hundred times, and reach 100 GW until 2015 (**Figure 4.11**). Since then, the sector's growth has maintained its excellent pace mainly due to the significant cost reductions of photovoltaic panels (more than 80% since 2010) and favorable policies of the European Union, in an effort to achieve its ambitious energy plans and reach 600 GW in solar capacity until 2030 (European Commission, n.d.).

According to **Figure 4.12**, the biggest investments have been made by Germany, Spain and Italy, followed by the Netherlands, France and the UK, which all happen to be some of the continent's largest electricity producers and consumers. On the other hand, we see that the countries of northern Europe, tend to have comparatively smaller total capacities, as their high geographical latitude implies lower solar potential and less electricity produced.

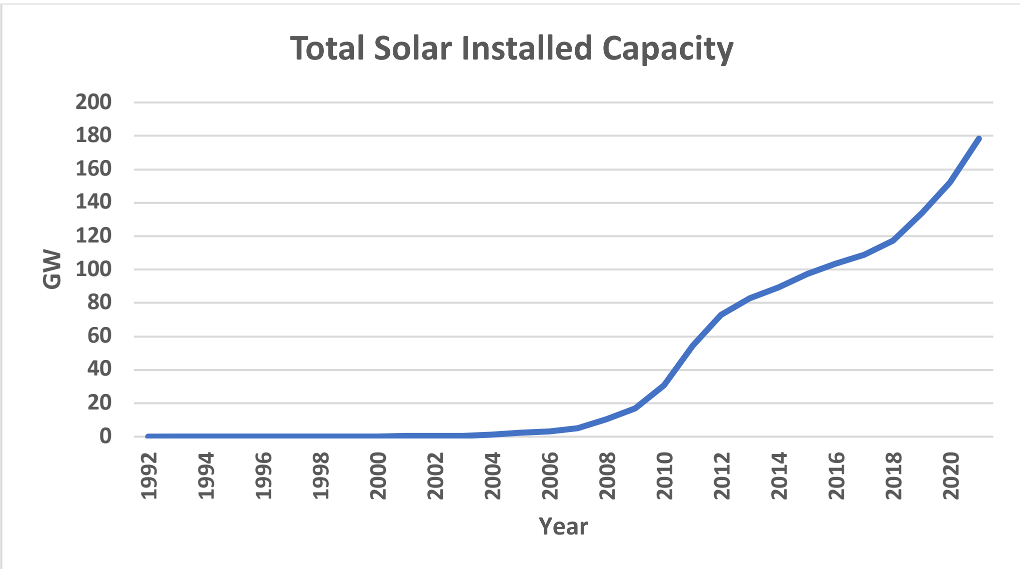

Figure 4.11: Change in the total Solar Generation Capacity of EU-27 plus Iceland, Norway and the UK.

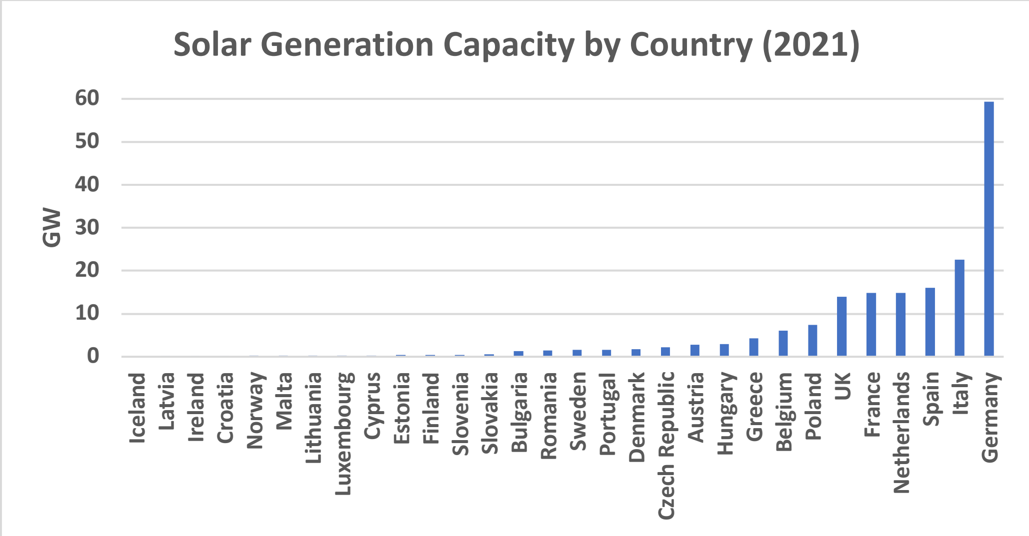

Figure 4.12: Solar Generation Capacity by Country (2021).

The following figure (**Figure 4.13**) shows the percentage of integration of solar power to each country's total capacity. As mentioned before, solar installations were introduced on a large scale after 2005 so their share to each system's capacity started becoming visible in the 2010s and took a big leap upwards during the 2020s. Currently, the Netherlands, Malta, Belgium, Germany Hungary and Greece have incorporated solar power to a percentage larger than 20% of their domestic generation capacity, while others like Norway Iceland and Latvia continue to have small shares as mentioned above.

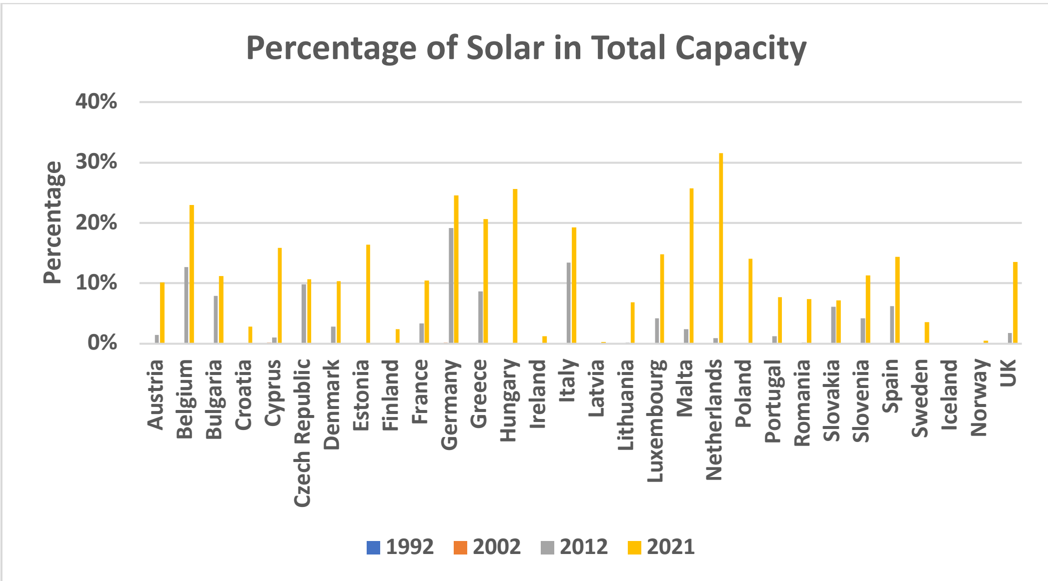

Figure 4.13: Change of solar as part of the total generation capacity.

In terms of electricity generation from photovoltaic systems, all the European countries have at some point increased the participation in their mix, although some of them maintain small shares. **Figures 4.14** and **4.15** present the percentage of generated electricity coming from solar power in 1992 and 2021 respectively. The maps indicate that countries of southern Europe have achieved largest increase in the shares of electricity produced by solar power due to the highest solar potential of the smaller latitudes; examples like Spain, Italy and Greece have moved from shares of practically 0% in 1992, to almost 10% in 2021.

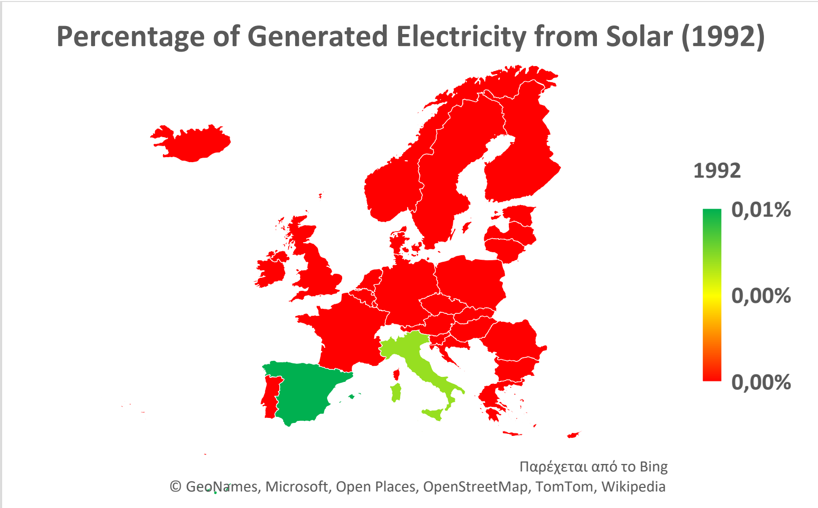

Figure 4.14: Percentage of Generated Electricity from Solar in Europe (1992).

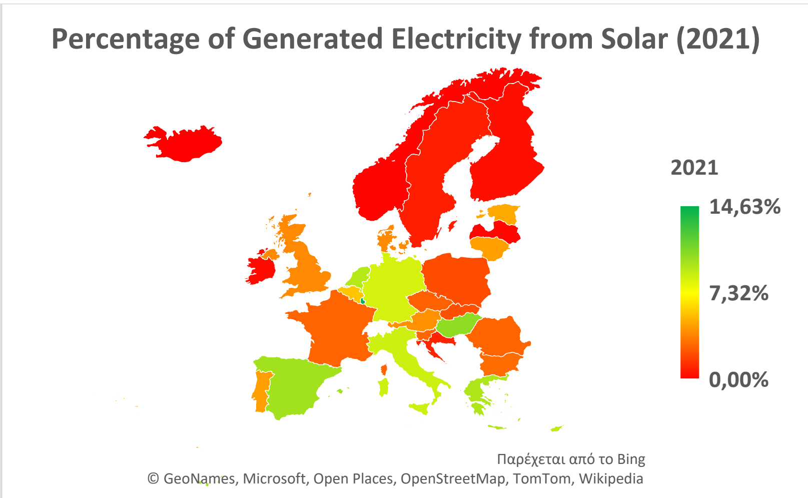

Figure 4.15: Percentage of Generated Electricity from Solar in Europe (2021).

4.5 Renewables in total

The European countries, motivated by the need to reduce greenhouse gas emissions and thanks to the improvements in technology, are gradually shifting to a more sustainable energy system. Therefore, the wide expansion of the renewable sources of energy has transformed the landscape of electricity generation since 1990.

In terms of both generation capacity and electricity produced, until the end of the 1990s, renewable energy's portion was principally dominated by hydropower as electricity production from other renewable sources hadn't yet matured. Nevertheless, the new millennium brought significant changes in technology and energy policies making variable renewables flourish and grow at an exponential pace. **Figure 4.16** demonstrates the change in total renewable installed capacity of the countries we study; we see the first years until 2000 that have relatively stable values (mainly supported by hydropower installations) followed by the rapid growth in capacity during the integration of solar and wind power.

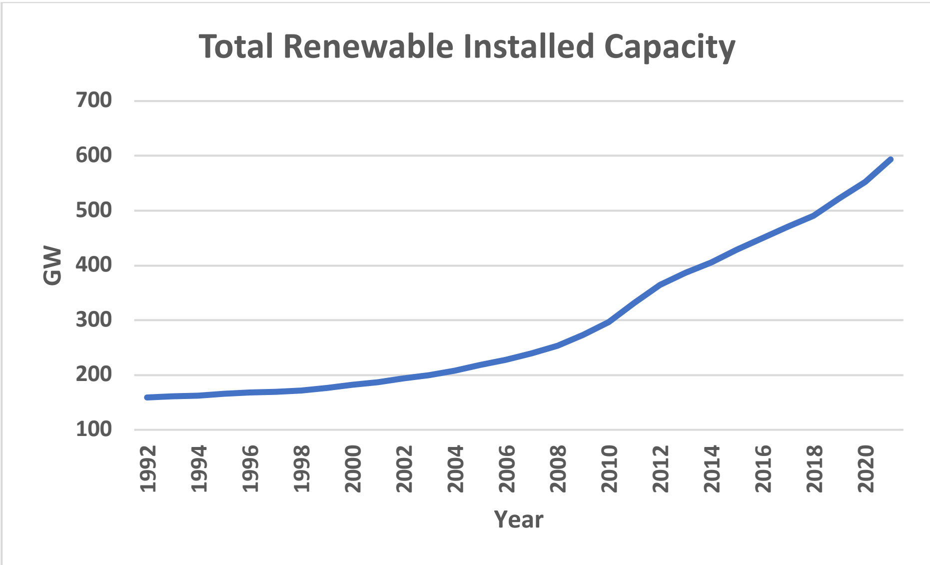

Figure 4.16: Change in the total Renewable Generation Capacity of EU-27 plus Iceland, Norway and the UK.

In **Figure 4.17** is shown the percentage of integration of renewable power into each country's total capacity. As expected, most of the countries show an increase over the years, with some of them reaching a share higher than 60%. These include Norway, Iceland, Austria and others and the main reason is the large amount of hydro in their systems. It is of great interest, that Latvia is the only country whose share in renewables drops over the years. This could be explained considering its small size and the fact that until the 2010s it continued investing in natural gas thermal plants at a higher rate than in renewables, although in terms of generated electricity participation of renewables has also increased.

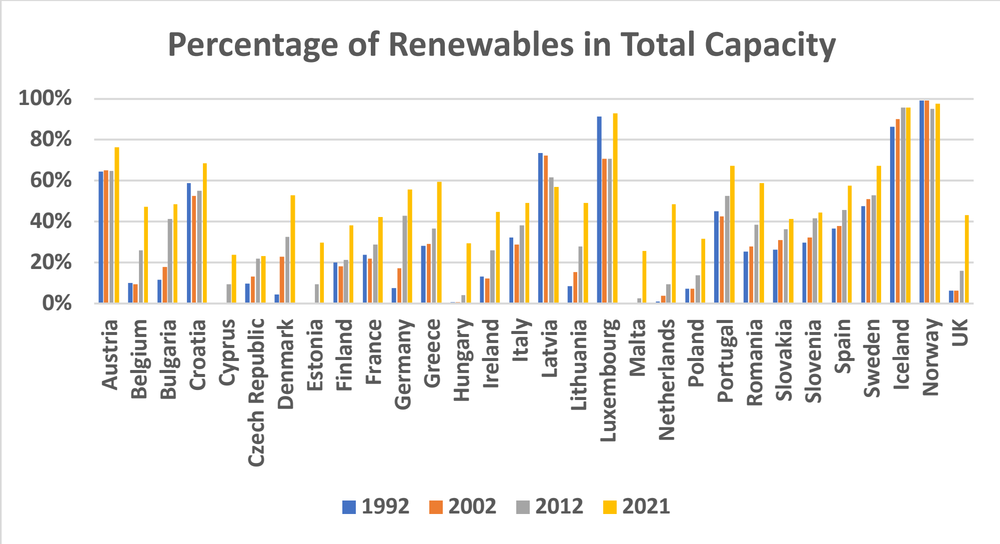

Figure 4.17: Change of renewables as part of the total generation capacity.

The next figure shows the change in the composition of the generation capacity between 1992 and 2021 for the 30 countries we study cumulatively (**Figure 4.18**). We see that today renewables are the dominant source in terms of installed capacity as they have already doubled their share from a 24% during 1992 to a 52% in 2021. On the other hand, fossil fuels show a large decline from 56% to 38%, and nuclear power from 20% in 1992 is now down to half representing only one tenth of the total capacity in 2021.

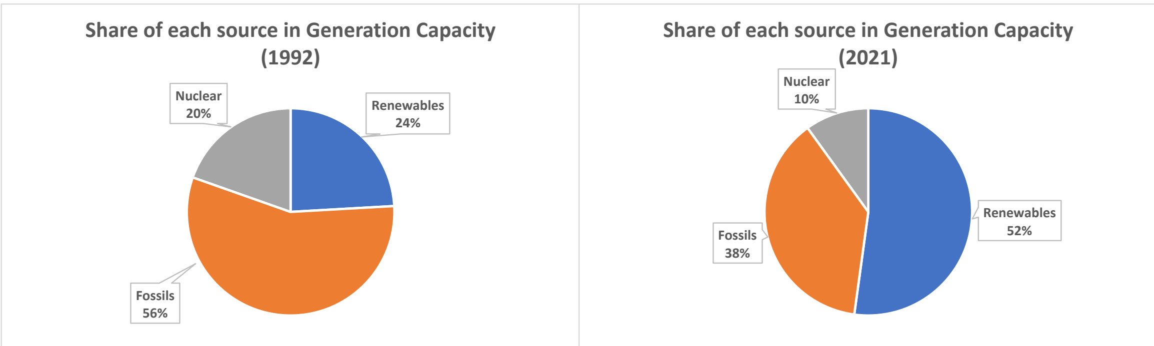

Figure 4.18: Generation Capacity by Source in 1992 and 2021.

The same trends of increase in renewables and fall in combustibles and nuclear are observed in the amount of electricity generated (**Figure 4.19**). Renewables have moved from an annual production of 500 TWh -during the period when only hydropower was used extensively- to almost the triple value in the beginning of the current decade surpassing fossil fuels, which for a long time remained the principal source of electric power in Europe.

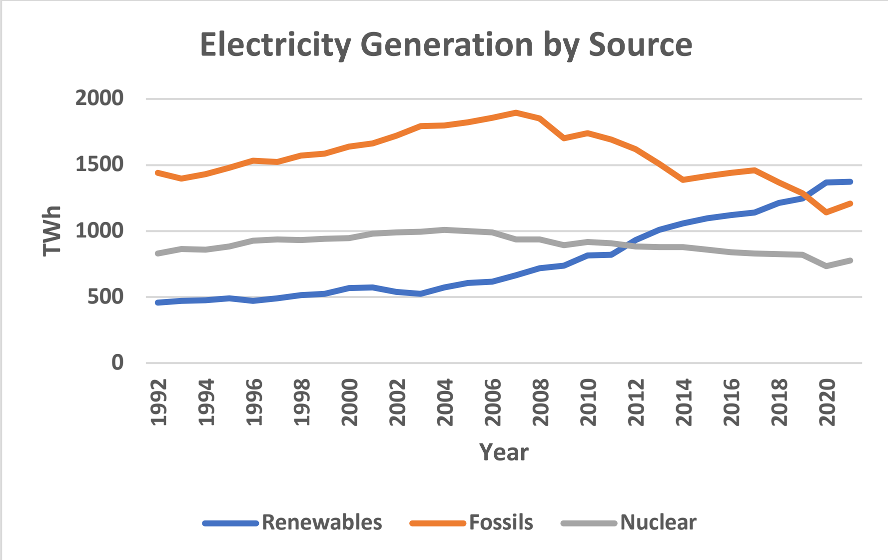

Figure 4.19: Electricity Generation by Source since 1992.

Overall, the incorporation of renewable sources into each country's electricity mix is progressing very rapidly, and all the European countries have significantly increased the percentage of their domestically produced electricity that comes from renewables during the last 30 years.

Figures 4.20 and **4.21** depict that change in the share from 1992 to 2021 for each country separately. It is visible that except for countries like Norway and Iceland -that already depended on renewables in the 1990s for electricity generation- the others have managed to integrate at impressive rates renewable electricity into their generation mix. As of today 21, (more than two thirds) of the European countries listed below generate at least one third of their electricity exclusively from renewable sources, compared to only 7 countries in 2021, with the trend showing that even more will reach that share in the near future.

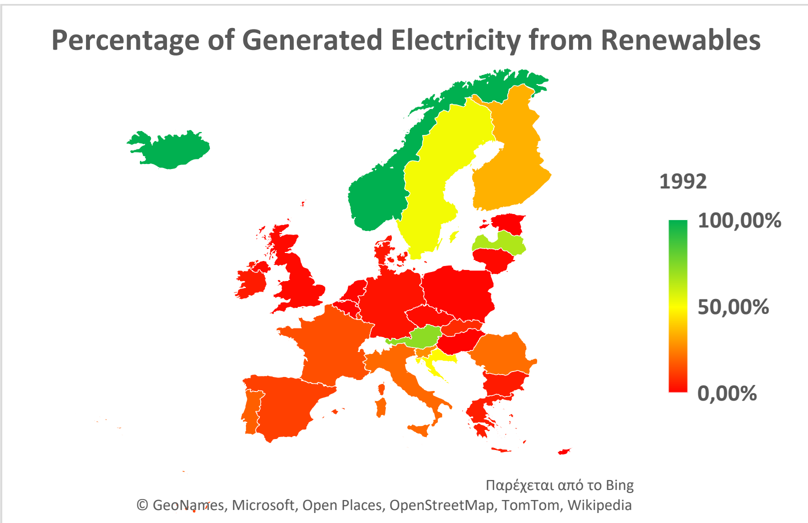

Figure 4.20: Percentage of Generated Electricity from Renewables in Europe (1992).

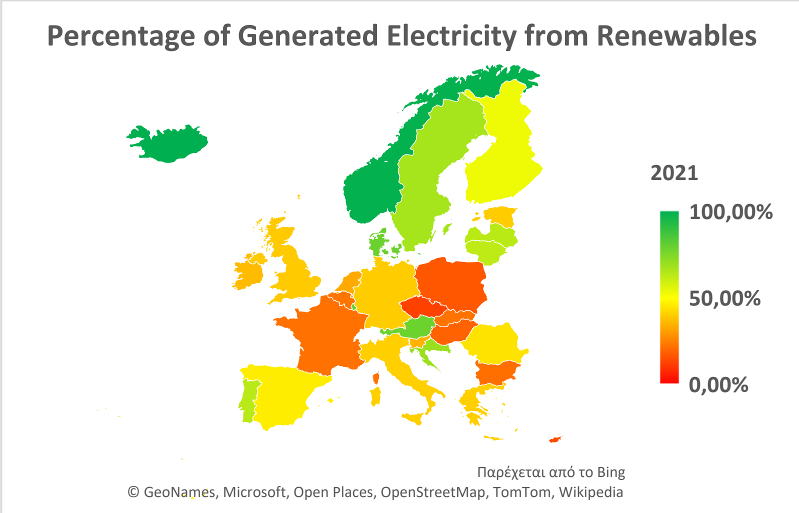

Figure 4.21: Percentage of Generated Electricity from Renewables in Europe (2021).

Chapter 5: Changes in capacity factors

5.1 Introduction

The capacity factor can be affected by a variety of factors. Specifically, the type of the power plant and the primary energy source are key determinants; renewable sources, and especially variables like wind and solar power, tend to have comparatively lower capacity factors, principally due to the fluctuating nature and the availability of the resources. Refueling, unplanned shutdowns and scheduled maintenance are also principal drivers, as frequent and long-term breakdowns lead to smaller values of the capacity factor (Muratori et al., 2017). Finally, the capacity factor is also affected by operational decisions that are highly associated with each system's demand management and in general its energy policy.

Overall, the capacity factor is a performance metric, that quantifies the effectiveness of a power plant and it reflects the plant's contribution to the total electricity supply. In a way it constitutes the identity of each energy project. In a high level, its value can indicate the economic performance of the plant, as higher capacity factors mean a more consistent and reliable electricity supply, making the project more efficient in terms of costs related to it.

This chapter is dedicated to the changes the capacity factors have undergone during the last 30 years all over Europe. The capacity factors are listed by electricity source - including fossil fuels, renewables and nuclear- and the data range from 1992 to 2021 following the previous chapters.

5.2 Renewables

5.2.1 Hydro

As already mentioned in a previous chapter, there are a few ways to classify hydroelectric power plants. The first one is by taking into account the plant's size and depending on its total installed capacity describe it as small or large, according to each country's (or region's) legislation. The small hydro definition varies between 2.5 and 25 MW but generally the most widely accepted value is up to 10 MW (Paish, 2002). The other way is by the type of its scheme; if it has storage capacity -with or without pumped storage ability- or is run-off-river. In most cases, run-off-river hydropower plants and plants with small storage ability are small scale while plants with reservoirs are usually large scale (Irena, 2012).

The capacity factor of hydropower plants varies a lot compared to other -renewable and not- technologies, mainly due to the flexibility that the different types of power plants offer. For instance, capacity factors of small-scale projects (and more specifically run-off-river) tend to vary, as the water flows present seasonal changes, and the lack of storage capacity creates operational constraints. This way of operation has a small flexibility in terms of the chronical distribution of the total generated electricity as the power is produced when available and not when needed. On the other hand, large hydropower reservoirs are more flexible, as the production of electric power is more controllable thanks to their ability to store the water. Hence, it is easy to operate both as baseload power plants offering fixed amounts of electricity to the system, and most importantly as peak-load power facilities, by providing electricity only to cover the demand during the peak hours (Irena, 2012). Overall, the way hydropower plants operate, is a choice taken in the framework of the strategic planning of each country's electricity system, and in the case of larger plants, the capacity factor is smaller if they operate as peak-load and larger if they are designed as baseload energy infrastructure.

The total capacity factor of hydropower varies a lot across the countries of the European continent as it is highly affected by the energy policy and the availability of water resources of each country. **Figure 5.1** demonstrates the average values the hydro capacity factor takes during each one of the three decades we study. We see that Iceland, Norway, Finland and Sweden have the highest hydro capacity factors, with Iceland exceeding 0.70 during the decade 2012-2021; the outputs are totally reasonable as most of these countries use hydropower as their main source of electricity.

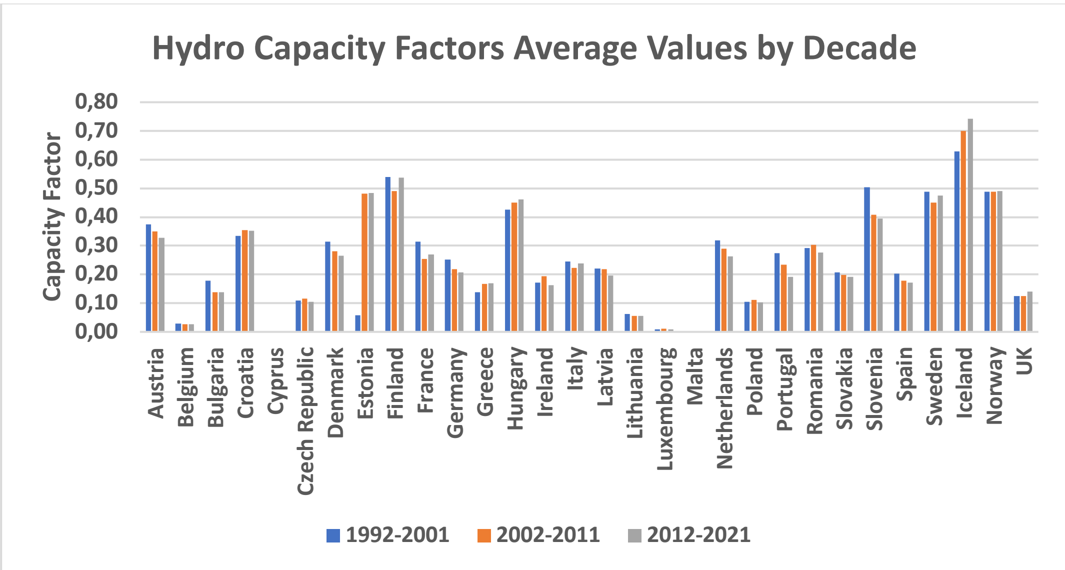

Figure 5.1: Change of hydro capacity factor by decade in selected European countries.

Assuming that capacity factors larger than 0.30 indicate that the country's power plants are used as baseload projects, we see that one third of the countries below use hydropower as base infrastructure for electricity generation. As expected, countries where the average annual precipitations are higher, and the topography favors the construction of large, dammed reservoirs, present the following characteristics: they have a larger integration of hydropower to their electricity mix and at the same time the highest values of hydro capacity factor, with Austria, Croatia and Slovenia being typical examples along with the ones mentioned above. One interesting exception is Hungary which -while being a country without extensive hydro installations- has had capacity factors above 0.40 during the last thirty years, and that's probably because its few hydropower plants that are exclusively small scale and mainly run-off-river, have sufficient water flows that allow them to operate during a reasonable amount of time annually. The other countries' capacity factors vary between 0.05 and 0.25, as they use their facilities mainly as peak-load power stations. **Figure 5.2** captures these variations across Europe, as the map shows the average hydro capacity factors by country during the last of the decades studied.

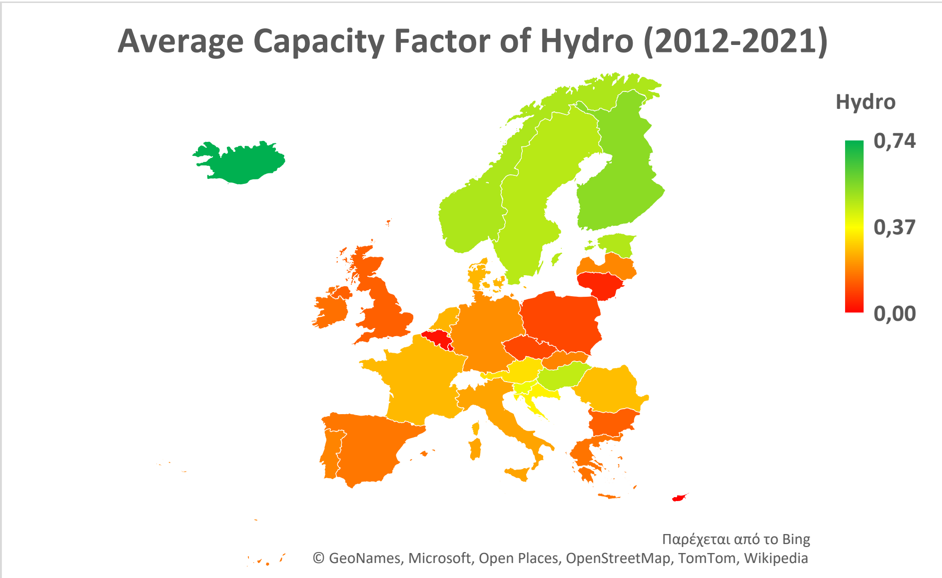

Figure 5.2: Capacity factors of hydropower in Europe during the decade 2012-2021.

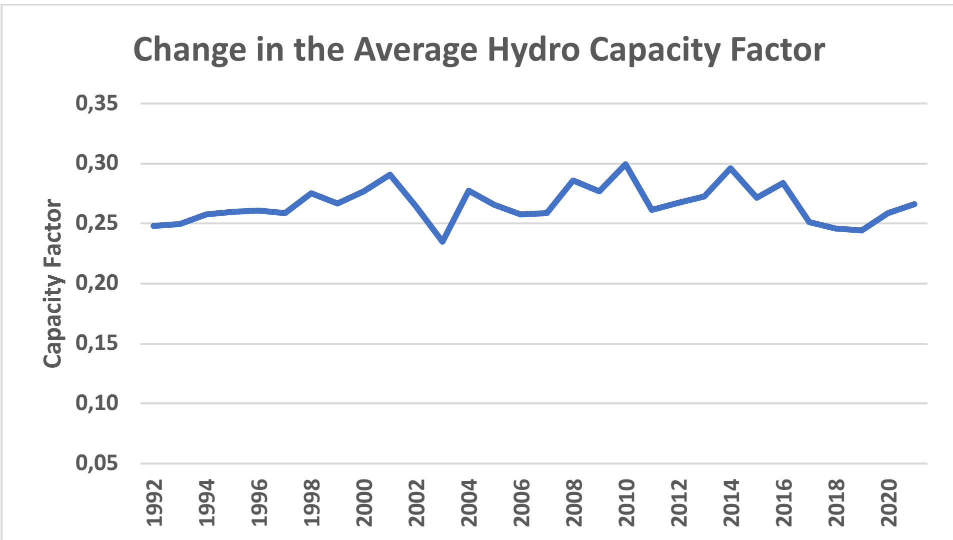

Figure 5.3: Change in the average hydro capacity factor of EU-27 plus Iceland, Norway and the UK.

The values of the capacity factors of each separate country have remained relatively stable during the last 30 years and have even presented a small decline in a few countries, as the gradual integration of variable renewables has led to higher electricity production from wind and solar, leaving a smaller share of development for hydro. Overall, the average hydro capacity factor of the European countries we study has maintained its value more or less around 0.27 with small variations as seen in **Figure 5.3**. That happens principally because the increase of the total hydro installed capacity and hydro electricity production have the same rate so the ratio between the two remains the same. Finally, it indicates that hydropower in Europe functions as a backup source, mostly used to enhance energy security and cover the electricity needs during the peaks in demand rather than a baseload source of electric power.

5.2.2 Wind

Electric power produced from wind, has shown a dramatic increase over the past 20 years and is now the leading non-hydro renewable source of energy. The amount of electricity generated from wind power installations today depends on many parameters, like the characteristics of the wind turbines and the properties of the wind resources of each area (Abed & El-Mallah, 1997), and differs a lot compared to the past mainly thanks to the technological advancements in the sector. Since the capacity factor is partially determined by the electricity production, all the above affect its value significantly.

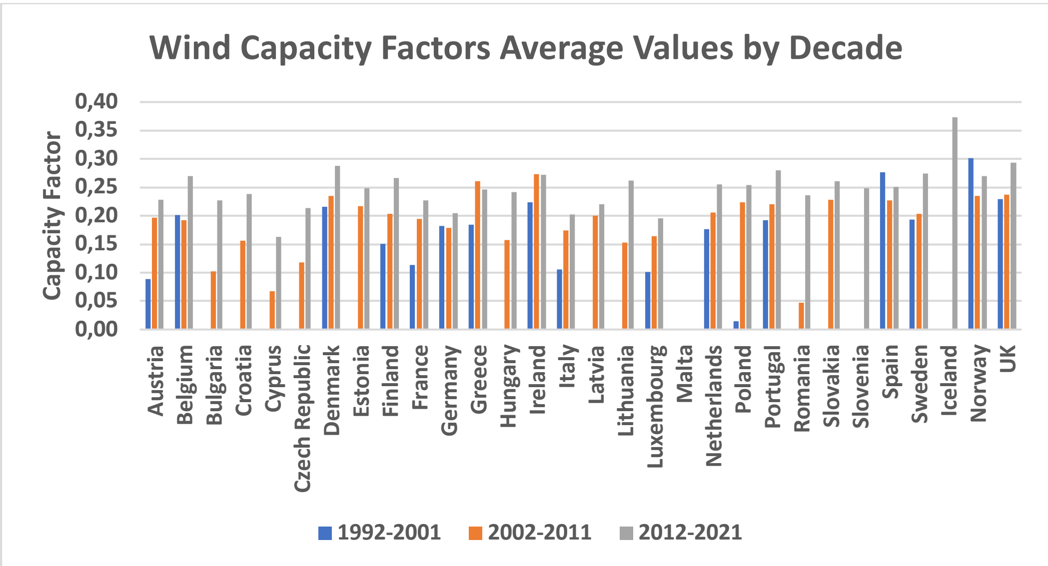

Figure 5.4: Change of wind capacity factor by decade in selected European countries.

Firstly, the improvements in the wind power technology have made the turbines more efficient and have allowed them to operate over a larger span of wind speeds, increasing the total period of generation and at the same time the capacity factor. **Figure 5.4** demonstrates the average wind power capacity factors by decade for each one of the countries members of the European Union along with Iceland, Norway and the United Kingdom. We can see that the values follow an ascending trend moving from average capacity factors of 0.15 in the 1990s to 0.25 during the last one of the three decades.

According to the theoretical wind power equation, electricity generation depends on the wind speed, and the geographical location is also a key determinant of the amount of energy produced and by extension the value of the capacity factor. For the same installed capacity, a wind turbine would possibly produce more electricity and have a larger capacity factor if it was placed in a region with high wind potential, than in a region with lower average wind speeds (assuming that the average wind speeds would not exceed the shutdown limits of the turbines that exist for technical and safety reasons).

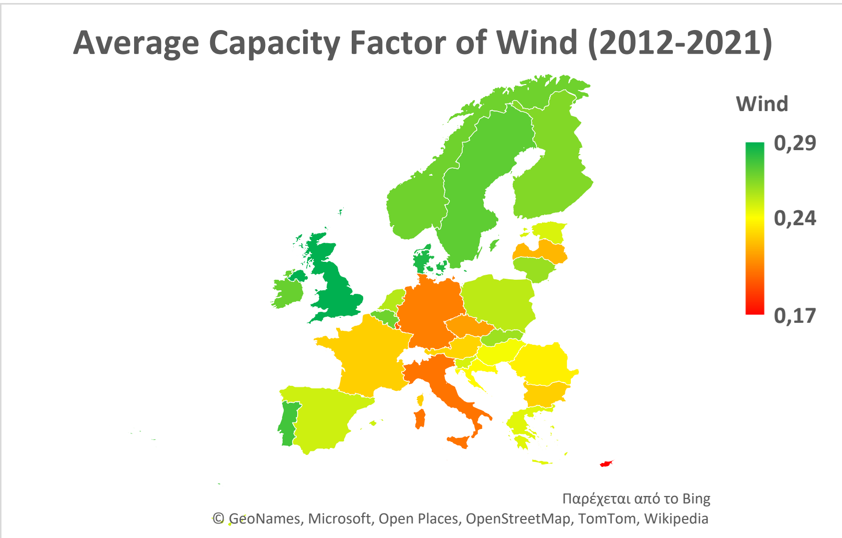

Figure 5.5: Capacity factors of wind power in Europe during the decade 2012-2021.

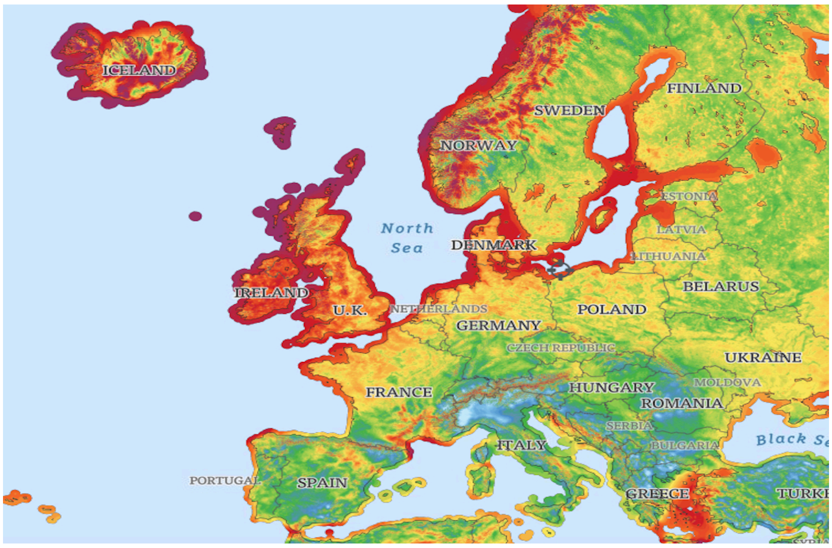

Figure 5.6: Average wind speeds in Europe. The red color indicates higher speeds (Global Wind Atlas).

Figure 5.5 presents the average wind capacity factor of each European country during the decade 2012-2021, while **Figure 5.6** shows the average wind speeds across Europe. By examining, we observe higher speeds along the Atlantic Ocean, the North Sea, the British Isles and the Aegean Sea (Enevoldsen et al., 2019) and as expected the capacity factors of these regions take larger values. Therefore, countries like Denmark, the United Kingdom, the Nordic Countries, Portugal and Greece have the highest capacity factors across Europe.

Apart from the above, the capacity factor is also affected by the characteristics of the wind turbines and their position compared to the land with the latter practically being the parameter of geographical location; offshore wind farms tend to have higher capacity factors, as above the sea there are no obstacles, and the wind speeds are higher (Irena, 2012). Regarding the turbines' characteristics, largest heights and largest blade lengths lead to higher electricity generation -as wind speeds increase with the altitude and the area of the turbines affects the power output- and at the same time higher capacity factors.

Overall, the average capacity factor of the wind power installations in Europe has presented a significant growth over the years and has moved from values close to 0.15 in the 1990s to 0.25 in the most recent years as seen in **Figure 5.7**. Today there are many countries above and some below that average but in general the capacity factors have increased thanks to the continuous improvements in technologies that allowed the fast-paced development of this source of electricity.

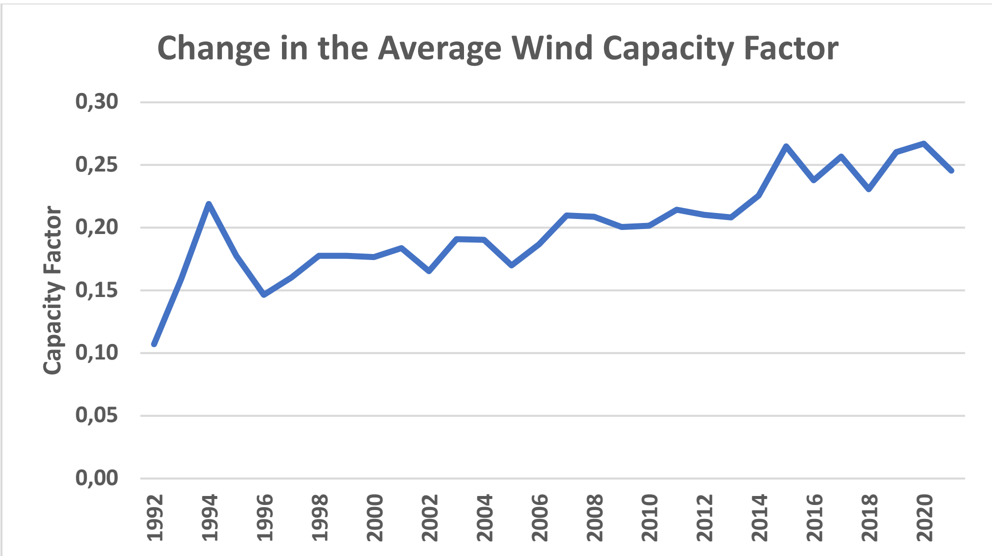

Figure 5.7: Change in the average wind capacity factor of EU-27 plus Iceland, Norway and the UK.

5.2.3 Solar

The use of solar power for electricity production has shown an exponential increase in the last 15 years in Europe. It is a variable renewable energy source (along with wind power) as the nature and the availability of its resources are more fluctuating compared to other renewables (e.g. hydropower with storage ability) and the electricity generation from this type of energy relies on sunlight availability. Consequently, the capacity factor of solar power plants also depends on the sun.

Generally, photovoltaic capacity factors take smaller values than other sources and typically range between 0.10 and 0.20. This could be explained because electricity is produced only during the day and considering that throughout the year, there are on average 12 hours of daylight and 12 hours of night each day, it is impossible for the solar panels to operate cumulatively more than half a year. So, the maximum capacity factor they could potentially achieve is no higher than 0.5. But daylight is not the only condition for the panels to operate with efficiency. The climatic conditions of a region are also key determinants to the operation of solar power plants, as more cloudy climates do not allow large amounts of sunlight to reach into the surface during the year, reducing the total functioning hours of the panels. The amount of solar irradiation and its angle compared to the ground also affect the generation and by extension the capacity factor. Finally, the technological progress made in solar panel technologies during the last decade has made them more efficient and has increased their capacity factor.

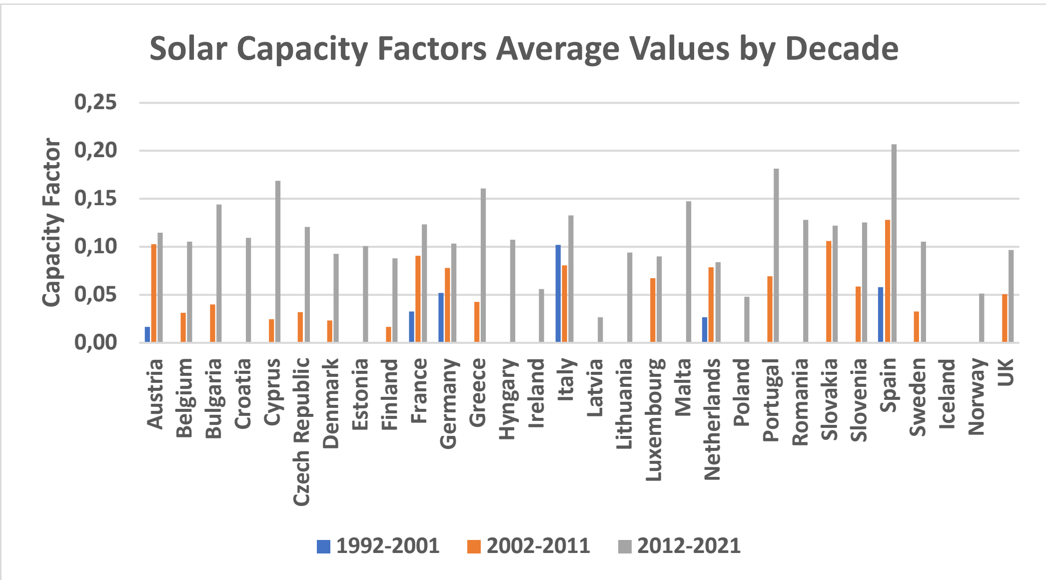

Figure 5.8: Change of solar capacity factor by decade in selected European countries.

Figure 5.8 shows the average solar capacity factors for each European country during each one of the three decades we studied. We see that only a few countries have measurable values during the first decade, mostly because of experimental solar projects, and show small capacity factors. As solar power is a relatively new source of electricity, it began to grow after the middle 2000s and the capacity factors followed an ascending rate from then on as the improvements in efficiency permitted largest amounts of electric power to be produced. The capacity factor increased in impressive numbers and in many countries it more than doubled, indicating the large development this source of energy achieved. Currently, the countries with the largest capacity factors in Europe are Spain, Portugal, Greece and Cyprus. **Figures 5.9** and **5.10** demonstrate the average solar capacity factor of each country during the decade 2012-2021, and the horizontal solar irradiation across Europe respectively. As expected, we observe that countries of southern Europe which have the smallest latitudes and receive larger amounts of radiation, have impressively larger capacity factors than the countries of the northern part of the continent.

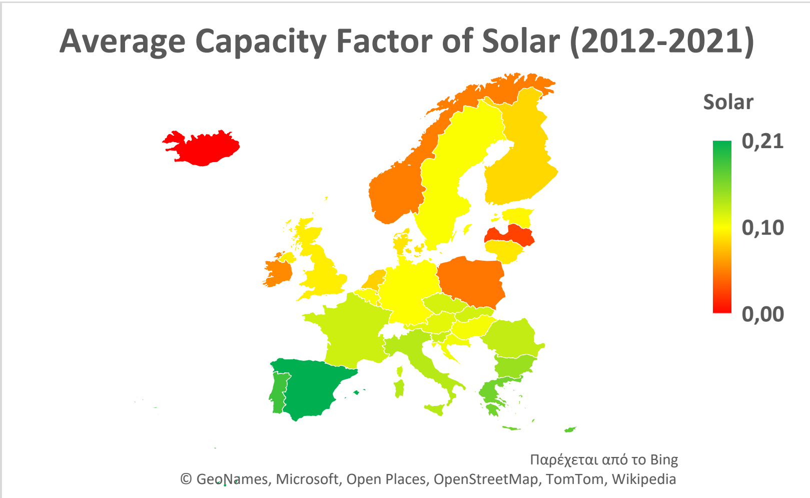

Figure 5.9: Capacity factors of solar power in Europe during the decade 2012-2021.

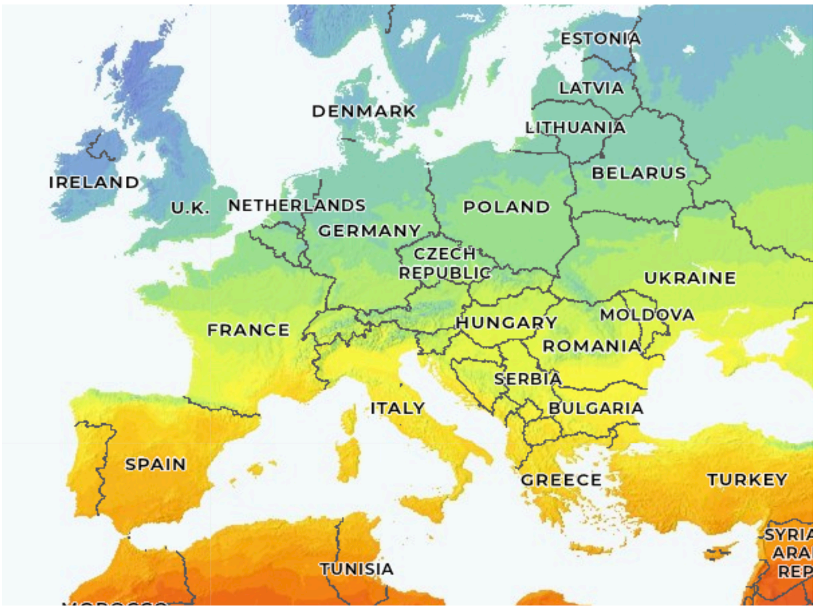

Figure 5.10: Horizontal solar irradiation in Europe. The red color indicates higher amounts of irradiation (Global Solar Atlas).

Overall, solar power's average capacity factor has shown an impressive growth in Europe since its initial launch into the continent's electricity systems. **Figure 5.11** shows that from average values of 0.02 until 2000, it has gradually exceeded 0.10 during the last decade mainly due to the improvements in solar panel efficiency. Today it has reached a fixed value of 0.12 with no visible trends for further increase. Therefore, the arising challenge for the solar sector in the near future will be the ability to develop further the technology around solar panels in order to achieve even larger capacity factors.

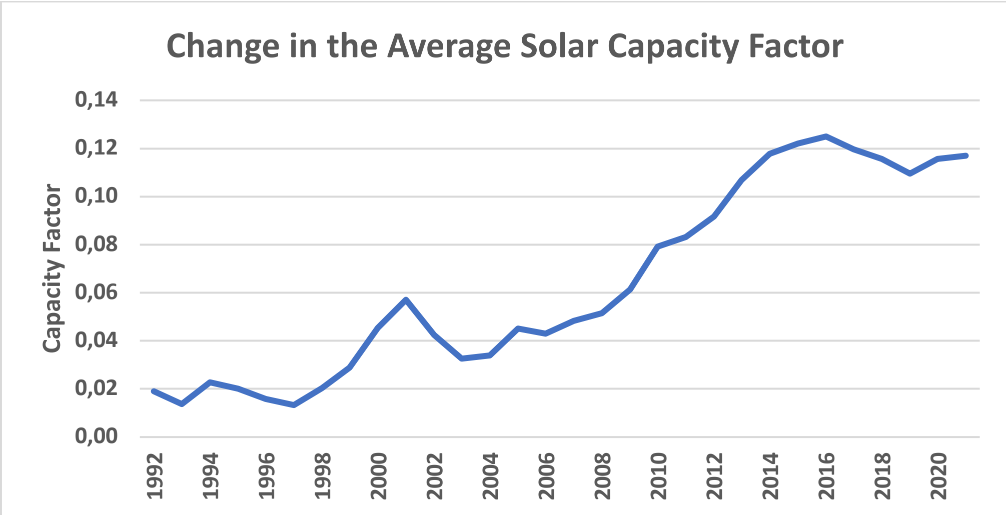

Figure 5.11: Change in the average solar capacity factor of EU-27 plus Iceland, Norway and the UK.

5.3 Nuclear

Along with renewables, nuclear sources are considered one of the most important tools for the reduction of CO_2 emissions of the energy sector (Pata & Samour, 2022), and until now have been used extensively by a number of European countries. Nuclear power plants have the ability to generate consistent and reliable supplies of electricity and enhance the energy security of each electricity system. The nuclear reactors typically have very high capacity factors compared to other low-carbon sources of electricity, as the continuous operation of the plants generates electricity during the largest part of the year -by providing baseload electricity- and they only stop during maintenance works or planned refueling outages.

In Europe, nuclear power plants have large capacity factors that historically vary between 0.75 and 0.85 as shown in **Figure 5.12**. From the graph we observe that only half of the studied countries use nuclear power, as many European states' policies are strongly anti-nuclear (World Nuclear Association, n.d.) but the ones using it have either stable or increasing numbers in their capacity factors especially after 2000. We see that most of the countries have great performance by having values that exceed

0.80 during the decade 2012-2021. In the case of Lithuania although, we see that despite the increasing trend, the capacity factors dropped to zero during the last decade, as the country decided to fully decommission its nuclear power plants from 2010 and afterward, when the electricity production from nuclear sources was abolished. On the other hand, countries like Finland score the best, having capacity factors close to 1.00, indicating the continuous and highly efficient operation of their nuclear facilities.

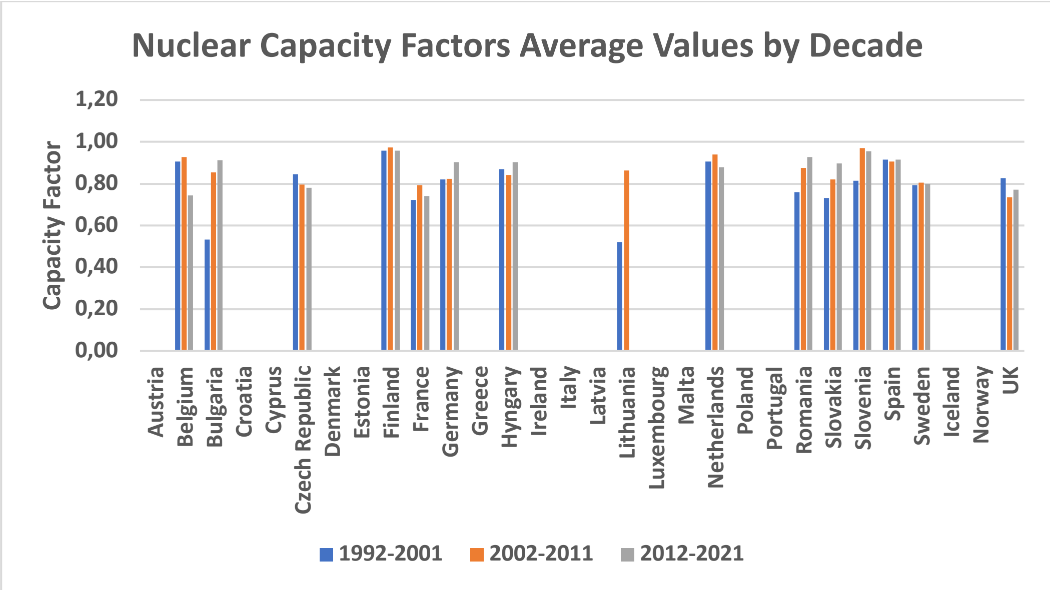

Figure 5.12: Change of nuclear capacity factor by decade in selected European countries.

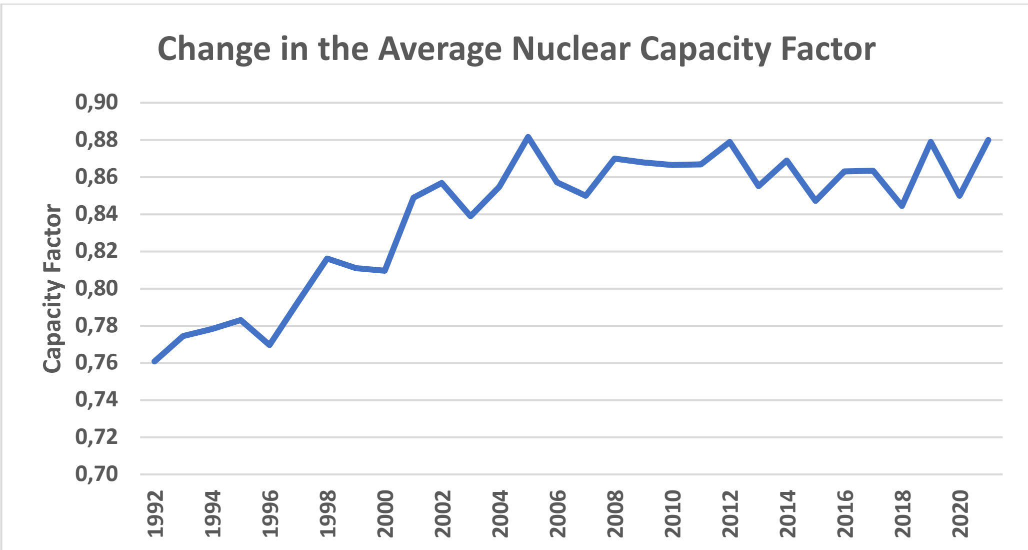

Figure 5.13: Change in the average nuclear capacity factor of EU-27 plus Iceland, Norway and the UK.

If we macroscopically look at the European continent, we will notice that the nuclear capacity factor began from an average of 0.78-0.80 in the first examined decade and stabilized to 0.86 during the last 15 years presenting a slight increase (**Figure 5.13**).

One possible interpretation could be the fact that the first attempts for the decarbonization of electricity production started in the 1990s and the (low-carbon) nuclear plants increased their generation -without a visible increase in the total capacity- resulting in a growth in the capacity factors. But after 2000, when solar and wind power started entering the European grids, the generation from nuclear plants was limited; and that combined with a small decrease in the total capacity -as countries like Lithuania started phasing out their plants- led to a stabilization of the nuclear capacity factor to the values seen above.

In summary, nuclear power facilities achieve larger capacity factors than other sources of energy and are suitable for baseload electricity infrastructure as they are reliable and secure the power supply. Nevertheless, nuclear energy faces challenges mainly because of the rapid integration of variable renewables into the system, that work as substitutes, compete with nuclear in the low-carbon emission race, and gain ground in a continent where half of the countries have already adopted no-nuclear policies.

5.4 Fossil Fuels

The term fossil fuels usually refers to a combination of primary energy sources like natural gas, coal and oil (petroleum) that are used to generate electric power in thermal power plants. As already described in Chapter 2, fossil fuels were for the largest part of European history the number one source of electricity, but today their use is being restricted because of their pollutive nature and their negative impact on global warming. Depending on the type, and the role of each source within each separate power grid (e.g. baseload, peak load, backup generation), fossil fuels show a range of capacity factors, which are affected by the demand for electricity supply and of course the energy policies of each country. In general, natural gas and coal plants have higher capacity factors as they are used as base electricity infrastructure, compared to oil fuelled facilities that usually operate to cover the demand during the peak hours. On conventional thermal plants that operate as baseload facilities, capacity factor usually does not depend on the time of the operation (as they are operating almost constantly throughout the year) but on the share of their nominal capacity that is being used.

The energy strategy between each European state differs a lot regarding the use of fossil fuels. As seen in **Figure 5.14**, there are countries that use conventional sources of electricity as their baseload power supply -including Portugal, Poland, Germany and Greece- and have capacity factors that exceed 0.50 and even 0.60 in some cases (Greece until the early 2010s). On the other hand, countries like France, Norway and Sweden that principally rely on nuclear and hydropower respectively, choose to have conventional power plants as a backup and take advantage of only a small part of their total capacity, resulting in significantly lower capacity factors.

If we take a closer look, we will notice that the capacity factors of fossil fuels have marked a significant decline in Europe during the last 30 years, as a result of the energy transition the continent undergoes. Most of the countries' values -including the ones with very high values like Germany and Greece- have decreased as a result of the gradual growth in the share of renewables; as the electricity covered by renewables continuously increases, conventional power plants operate less and less (Bolson et al., 2022). However, there are countries that haven't yet managed to integrate renewables at a large share into their systems, resulting in stable or even increasing values of the fossil capacity factors like Romania and Bulgaria respectively. A special case is Luxembourg, which shows large variations in each decade's average values. This is explained by the small size of the country and its mainly importing electricity policy, which makes it generate electric power only when necessary, making its capacity factors increase.

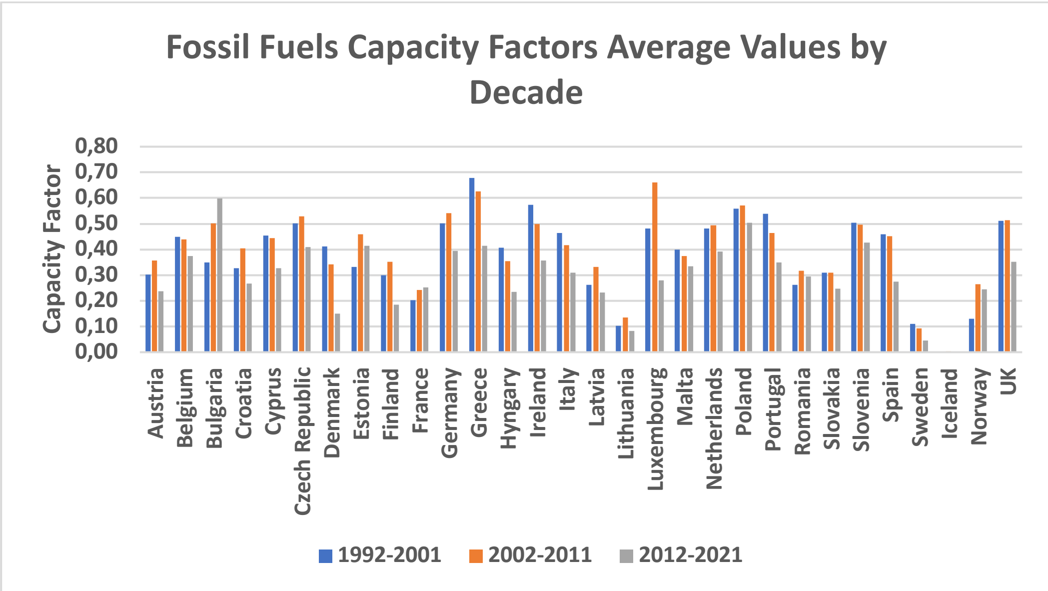

Figure 5.14: Change of fossil fuels capacity factor by decade in selected European countries.

Overall, the average fossil fuel capacity factor of the countries we study has shown an interesting evolution through the last three decades. As we see in **Figure 5.15**, for the first 15 years from 1992 to the late 2000s, it remained at an average value of around 0.40, while afterwards it started dropping and stabilized below 0.30 after the second half of the 2010s. The decreasing trend matches chronically with the large-scale integration of variable renewables into the European grids, and it was caused principally by the large reduction in coal generated electricity (as coal was up to then the principal conventional source of electricity and the one with the highest carbon emissions compared to oil and gas). However, the total installed capacity of fossil fuels increased, as new natural gas thermal plants were constructed to replace coal plants, while at the same time coal plants were not fully decommissioned and remained connected to most countries' grids as a backup plan for the supply security. This combination of smaller amounts of generated electric power with larger numbers of generation capacity led to a rapid decrease in the total average capacity factor of fossil fuels in Europe, which in a short period has been reduced by more than 25%.

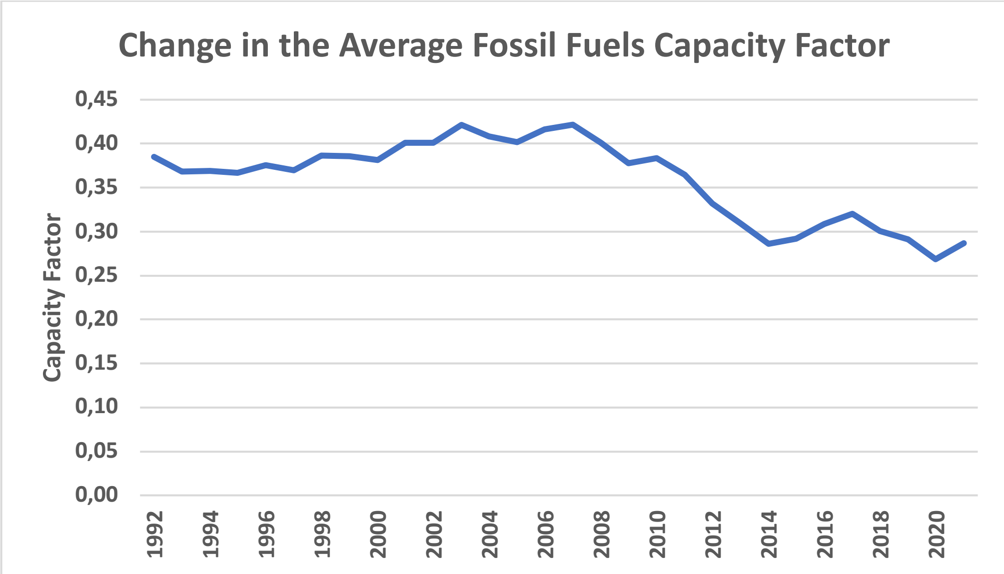

Figure 5.15: Change in the average fossil fuel capacity factor of EU-27 plus Iceland, Norway and the UK.

5.5 Total Capacity Factors

Having already seen the changes of the capacity factors at a source-concentrated level for each one of the European countries we can easily expand the term at a national level and investigate how the total capacity factor of each country has changed over the decades. As total capacity factor we consider the ratio of all the generated electricity in the country, to the potential electricity the total installed capacity of the system could produce regardless of the primary source.

The changes in the total capacity factor from 1990 and afterward vary between the European nations, but generally in most of the countries they follow the same trend. **Figure 5.16** shows the changes in their average values for each separate decade. We see that most countries follow the same pattern; they have stable or even slightly increased capacity factors between the first two decades and then they show a large drop, principally due to the wide introduction of variable renewable sources and the shift to cleaner electricity. This shift impacts the overall capacity factor, as wind and solar facilities typically have lower capacity factors. We spot countries like Belgium, Hungary, Germany, Poland and others with traditionally high values of capacity factor, to have significantly reduced the used amount of their total generation capacity and in most cases drop even below 0.40. On the other hand, we see that countries like

Bulgaria and Iceland have increased their total capacity factor as they have not yet integrated considerable amounts of variables into their systems; the first one is still strongly dependent on fossil fuels and nuclear power while the latter uses hydroelectric and geothermal power almost exclusively. **Figure 5.17** projects the changes in the average capacity factor of each country between the first and the last decade of our study. From the map we can conclude that countries with smaller integration of variables have maintained or slightly increased their values.

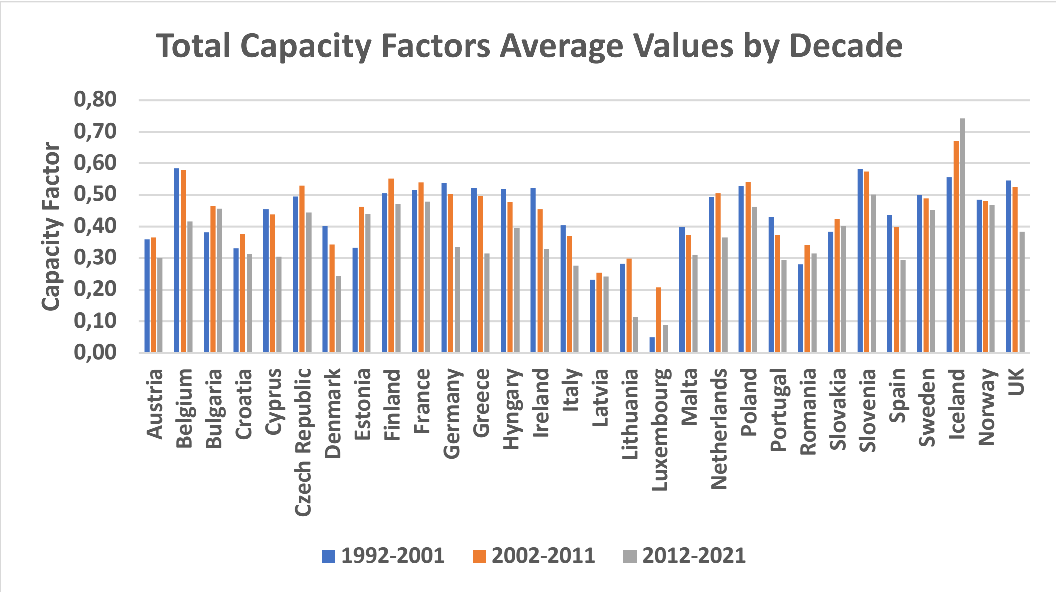

Figure 5.16: Change of total capacity factor by decade in selected European countries.

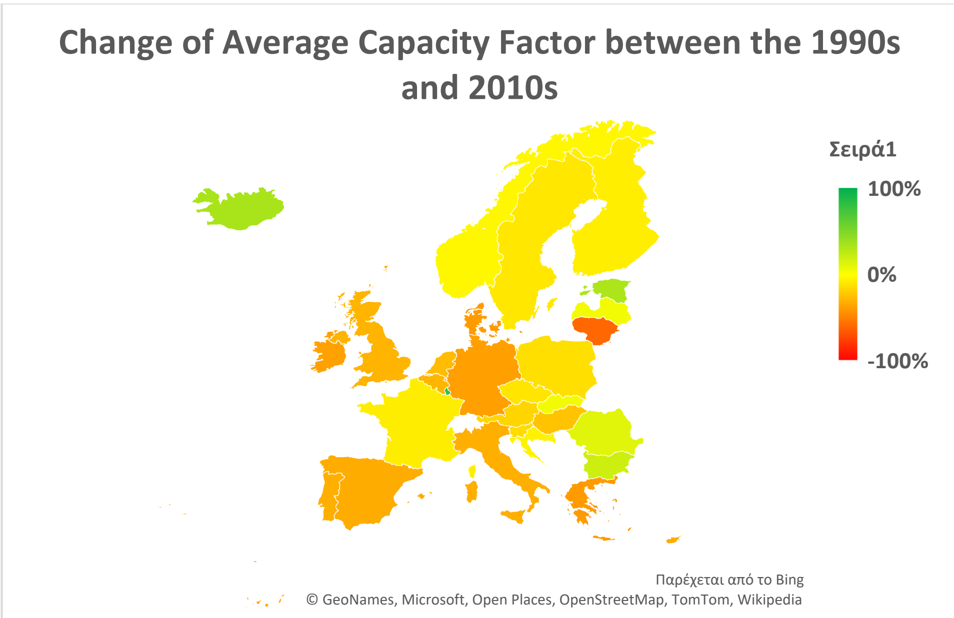

Figure 5.17: Change of Average Capacity Factor between the 1990s and 2010s.

Another interesting conclusion is that countries that are mainly importers of electricity like Luxembourg, Latvia and Lithuania, have very small capacity factors as their well interconnected grids allow them to import their energy needs and use their installed capacity only as backups.

Overall, the European continent as a whole shows the same changes that were mentioned before. The average value of the capacity factor was at a fixed level of more or less 0.45 until 2008, when it started decreasing and reached 0.35 in 2021 (**Figure 5.18**). This can be explained by considering that the rise of variable renewables adds more to the total generation capacity of the European system. At the same time, most of the countries are trying to phase out their conventional facilities and more specifically their coal power plants in an effort to produce low-carbon electricity; they reduce their operation but without fully decommissioning them and they keep the capacity to the grid as a way to enhance the electricity security. However, the total demand for electric power in Europe has remained stable and hasn't increased at all, causing the total capacity factor to drop. The result is that the share of installed capacity does not correspond to the share of electricity generated and it is a result of the exponential participation of renewables in the energy mix. As more solar and wind are added to the energy system, they will reduce the total capacity factor (Bolson et al., 2022).

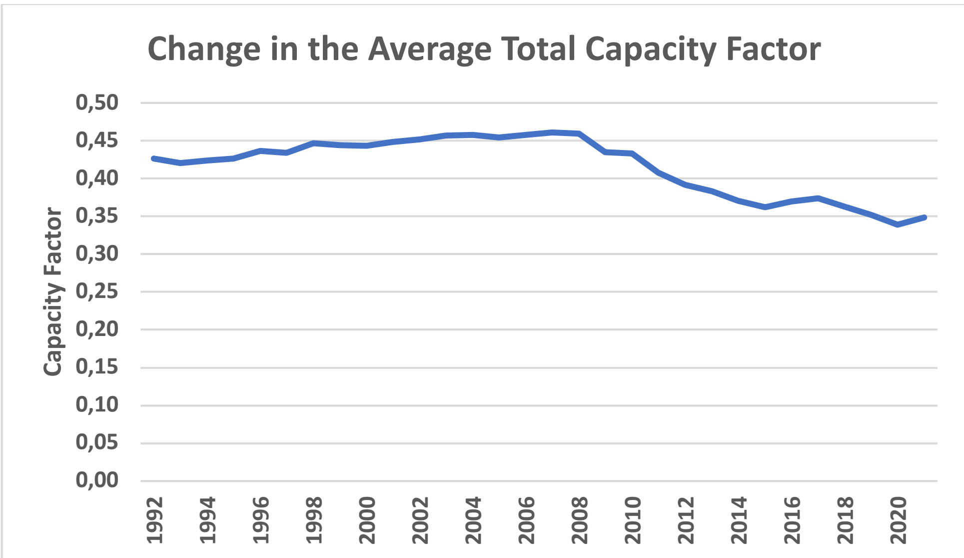

Figure 5.18: Change in the average total capacity factor of EU-27 plus Iceland, Norway and the UK.

From the above we can conclude that the gradual increase of the share of renewables in the European electricity mix has caused the total capacity factors to decline over time. This can be confirmed by plotting the values of the total capacity factor between 1992 and 2021 against the percentage of renewable sources as part of the total generation capacity of Europe. **Figure 5.19** shows a very strong negative correlation between the two with an R^2 of more than 0.81.

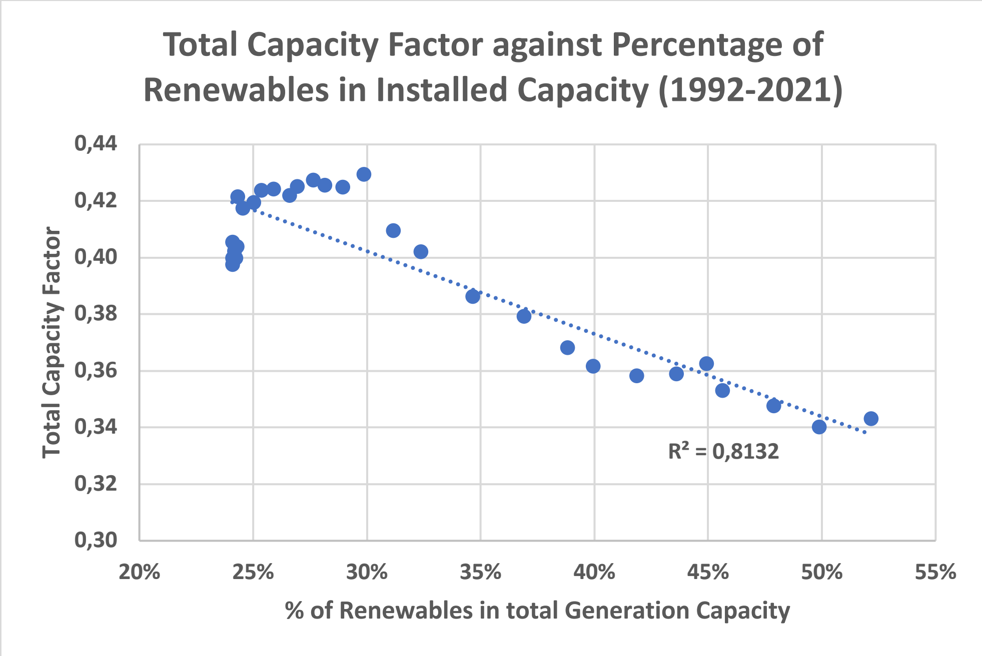

Figure 5.19: Total Capacity Factor against Percentage of Renewables in Installed Capacity (1992-2021).

If we do the same not taking in mind the first decade of our data -when the only renewables to the system were hydro- we see an even stronger correlation between the two values with an R^2 that exceeds 0.94, confirming the strong relation between the increase of variable renewables and the decrease of the total capacity factor.

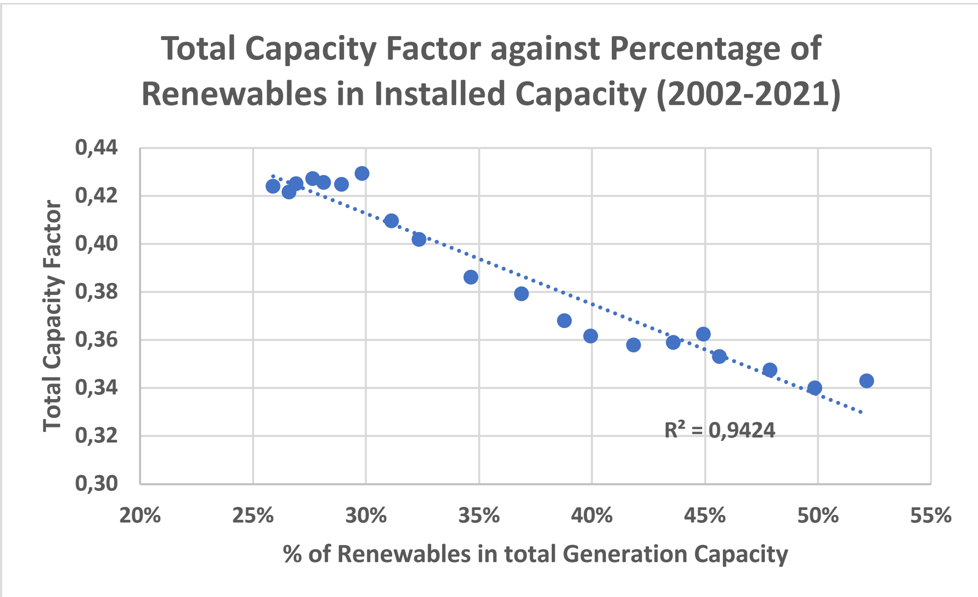

Figure 5.20: Total Capacity Factor against Percentage of Renewables in Installed Capacity (2002-2021).

Finally, it is worth mentioning that correlation does not imply that the capacity factor does not depend on other factors as well but shows a strong connection between the first and the integration of solar and wind power into Europe’s electricity systems.

Chapter 6: Economic approach in electricity domain

6.1 Introduction

The electricity components we analysed in the previous chapters -including the generation capacity, the electricity generation and demand, the composition of the electricity mix and the capacity factors- have undergone significant reforms during the last 30 years in Europe. They were examined by accounting for the changes in the use of each primary energy source for electricity generation driven by the energy policy of each European country. However, the largest part of the electricity domain is also affected by the economic performance of the continent and vice versa, so the examination from an economic perspective would produce useful conclusions.

In this chapter, we will try to investigate how the economy affects electric power, by examining the impact of basic economic indicators like the Gross Domestic Product (GDP) on electricity components. We will also try to find a relation between the electricity prices and changes in the sector.

6.2 The impact of GDP on electricity components

Gross domestic product, also known by its abbreviation as GDP, is the total monetary value of all goods and services produced by a country (or a region) during a specific period of time (usually it is measured on an annual basis). It is the most used way of measuring each country’s economic activity and performance. The division of the GDP with the total population of an area gives us the GDP per capita and it is a way of measuring and comparing the living standards between different regions.

As already mentioned, GDP indicates the economic growth of a country, and the increase in its value is a sign that an economy is doing well. In Europe, GDP has shown a significant increase from the 1990s and so has GDP per capita proportionally; considering that the European population has remained relatively stable over the last 30 years; an increase in the total GDP is translated as an increase in GDP per capita too. **Figure 6.1** demonstrates the evolution of the average per capita GDP of EU-27 plus Iceland, Norway and the United Kingdom from 1992 to 2021 (in current thousand US dollars). As we can see, from an average of 17,000$ during most of the 1990s, it showed a large increase in the 2000s and it stabilized in a range between 35 and 40 thousand US$ after 2010. It is worth mentioning that in this thesis we chose to work with nominal prices; current GDP refers to each specific year’s value and it is not adjusted for inflation, so its increase does not necessarily mean a real increase in a region’s output. However, Europe has had low and stable inflation rates from 1990 and afterward (at least until 2021) so we do not expect dramatic differences in the results.

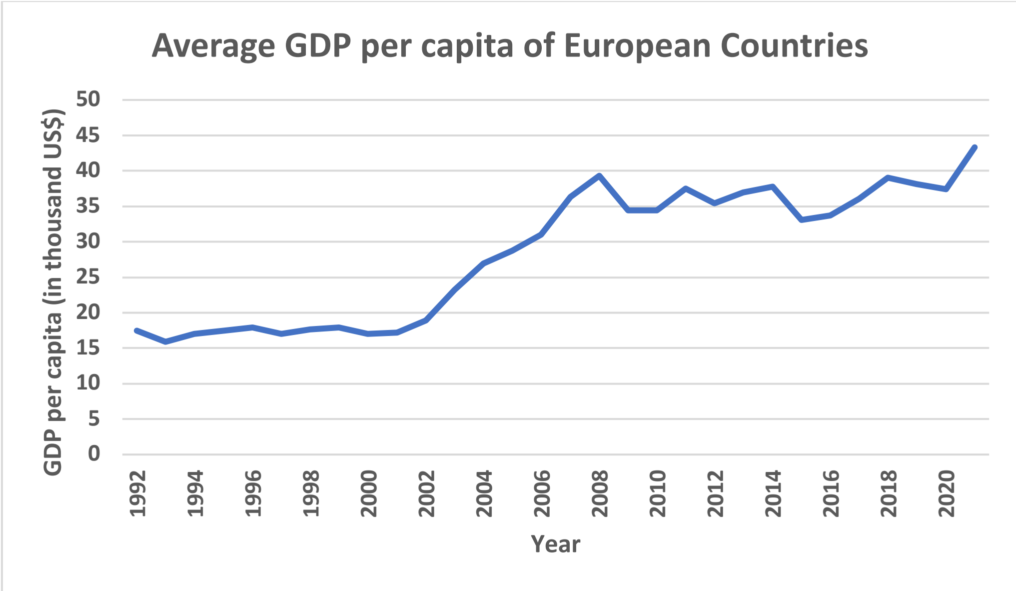

Figure 6.1: Average GDP per capita of EU-27 plus Iceland, Norway and the UK from 1992 to 2021 (in current thousand US$).

6.2.1 Electricity generation

The change in electricity generation of each country is affected by the consumption, and the demanded amount highly depends on the economic growth of the region. Economic growth often involves increased industrial activity, higher incomes and larger urbanization rates that eventually lead to an overall higher electricity consumption. As GDP in most cases indicates the performance of an economy, it is expected to have a strong relation with the energy demand and at the same time with the produced electricity.

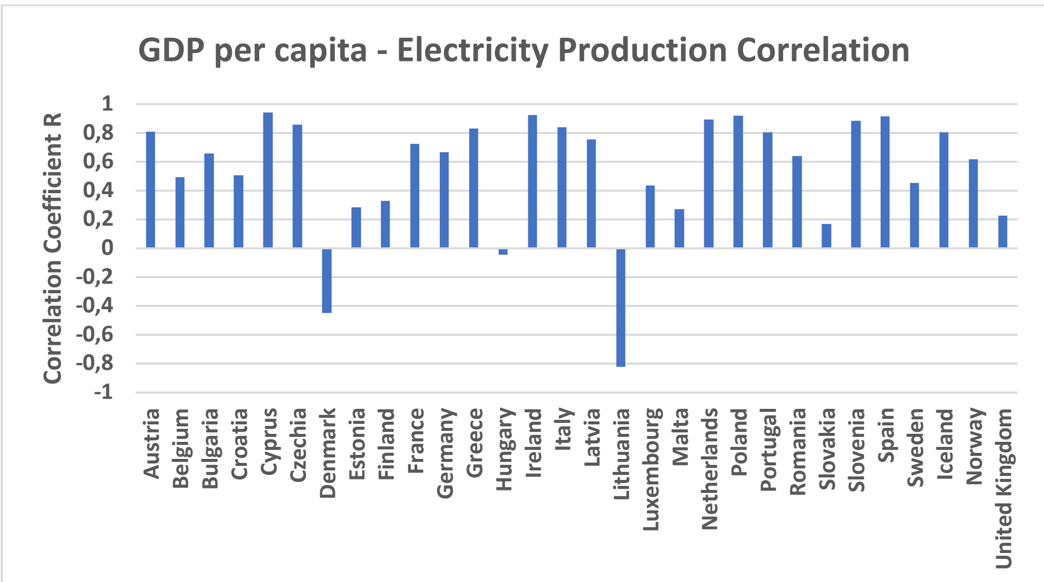

Figure 6.2: Correlation Coefficient R between per capita GDP and electricity generation for each country (from 1992 to 2021).

Figure 6.2 presents the correlation between the change in GDP per capita and electricity generation (from 1992 to 2021) for each one of the European countries we study. For the interpretation of the chart, we will consider that values of the correlation coefficient R between 0.3 and 0.5 indicate a medium relation, larger than 0.5 a strong relation and values from 0.75 and above show a very strong relation. We see that most of the countries we study present strong or very strong positive correlations, confirming that electricity generation increases when there is a growth in GDP. Exceptions include Denmark and Lithuania, which show medium and strong negative correlation respectively, meaning that while the economy is growing the produced electricity is decreasing. This can be easily explained considering that both countries' energy strategies took a turn at some time during the period we studied and started applying importing policies; they reduced the amount of domestically generated electricity, and they imported the rest to cover their demand, leading to smaller electricity production whilst on economic growth.

6.2.2 Total capacity factors

The relation between the average capacity factor of each country and the change in GDP is also of great interest. In **Figure 6.3** we see that many European countries have strong to very strong negative correlation between the two with only a few exceptions indicating that economic growth is linked to lower values of the total capacity factor of each county. The results are expected, since all European countries experience continuous growth in their GDP so countries with large investments in variable renewables (countries with large declines in their total capacity factors) are the ones with the highest correlation.

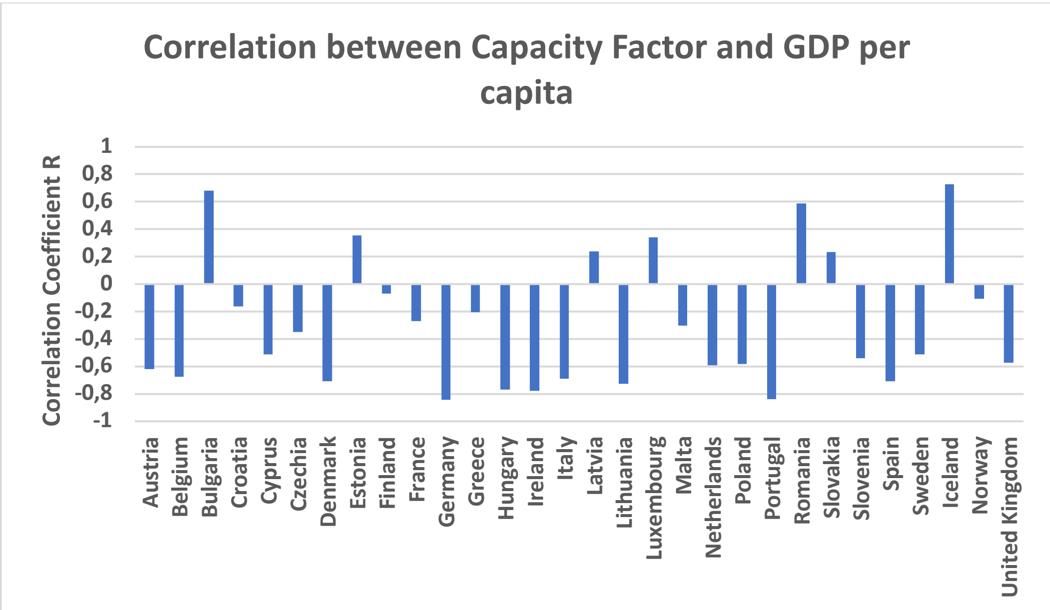

Figure 6.3: Correlation Coefficient R between per capita GDP and capacity factor for each country (from 1992 to 2021).

Exceptions include countries like Bulgaria, Romania and Iceland, which as analyzed in the previous chapter showed an increase in their capacity factors -as they have not yet integrated considerable amounts of variables into their systems- and for that reason have a positive correlation of their capacity factor with their per capita GDP. On the other hand, there are countries that show little to no relation at all between the two. Those among others, include Finland and France which despite their economic growth have maintained relatively stable capacity factors. A special case is Greece, which although following the trend of reducing capacity factors, has experienced different periods of economic growth and recession due to the country's long year economic crisis, resulting in no visible relation between GDP and capacity factor.

6.3 Changes in electricity prices

As already discussed in Chapter 2, the electricity market of Europe is divided into two separate segments (wholesale and retail market) and electricity prices in each one of them are determined by a variety of factors. Generally, retail prices include the cost of electricity production, so they are linked to the wholesale prices, but they also include fees, taxes and levies that vary between European countries. In this thesis, we choose to work with retail prices that refer to household consumers, since the data has a larger range compared to the ones of the wholesale market. **Figure 6.4** demonstrates the evolution of the average nominal electricity prices in €/kWh for domestic consumers in the European Union from 1992 to 2021, excluding all taxes and levies. These are the prices for households within the middle consumer category: Band Dc (Annual consumption up to 3500 KWh) for data prior to 2007 and Band Dc (Annual consumption between 2500 and 5000 KWh) from 2007 and later.

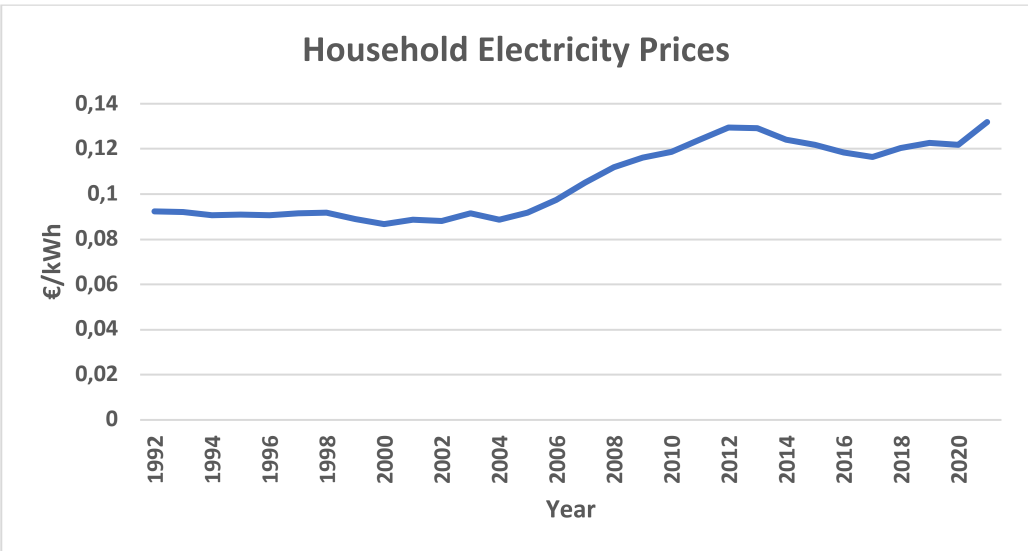

Figure 6.4: Average household electricity prices of of EU-27 from 1992 to 2021 (nominal, in €/kWh).

As we can see, from an average of less than 10 cents during most of the 1990s, the clear electricity prices for domestic users have increased significantly since 1998 (the year that marks the opening of the EU electricity markets) and they exceeded 12 cents after the early 2010s (Da Silva & Cerqueira, 2017). Respectively to the GDP (that was discussed above) we expect that the use of nominal electricity prices will not change dramatically the conclusions as there were small and stable inflation rates between 1992 and 2021.

6.3.1 Impact of GDP on electricity prices

The increase in per capita GDP seems to affect household electricity prices. As seen in **Figure 6.5**, the correlation between the two is very strong, as the coefficient of determination R^2 has a value that exceeds 0.82 (meaning an R larger than 0.90). From that we conclude that the clear electricity prices on end-users are associated with the economic growth in the European Union; an increase in the GDP per capita leads to an increase in the demand for electricity due to higher industrial activity and improved living standards, which eventually drives up electricity prices.

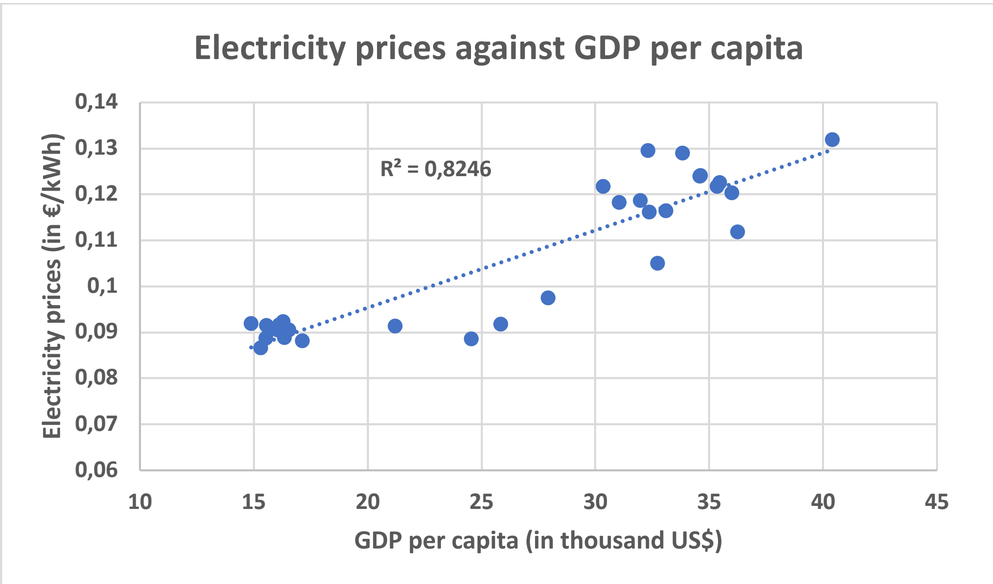

Figure 6.5: Household electricity prices plotted against GDP per capita only in EU-27 (1992-2021).

6.3.2 Impact of capacity factors on electricity prices

Since the large-scale introduction of variable renewable sources of electricity in the European systems around the 2000s and 2010s, the total capacity factors have shown a dramatic drop in the majority of the studied countries. The previous chapter showed the strength of the relation between the integration of solar and wind power into the European grids and the decrease in the capacity factors. So, the next step is to investigate if -and to what extent- the changes in the capacity factors (and by extension the shares of renewables) affect the prices of electric power in Europe. Using data from 1992 to 2021 we try to find out right below.

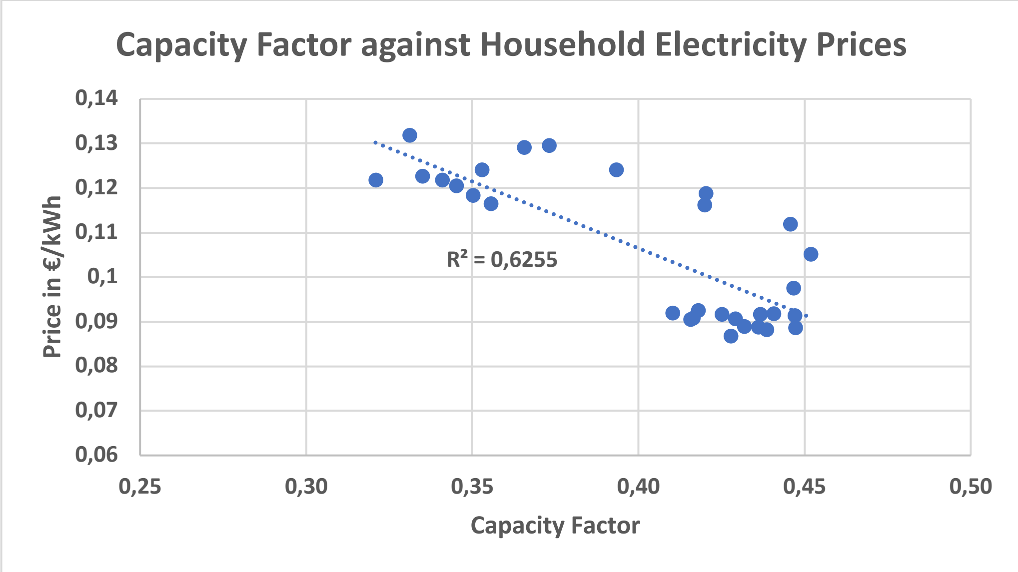

Figure 6.6: Household electricity prices plotted against the total average capacity factor only in EU-27 (1992-2021).

If we plot the household electricity prices against the total average capacity factor for each one of the years mentioned above, we will see the visible relation between the two (**Figure 6.6**). We see that there is a very strong negative correlation with an R^2 exceeding 0.62 (meaning a correlation coefficient R almost -0.80), meaning that the drop in the capacity factors leads to an increase in prices. It is worth mentioning that the correlation between them is influenced by a complex combination of generation mix, market dynamics, policy frameworks, and technological advancements. However, higher capacity factors indicate more efficient use of generation assets, contributing to stable and potentially lower electricity prices.

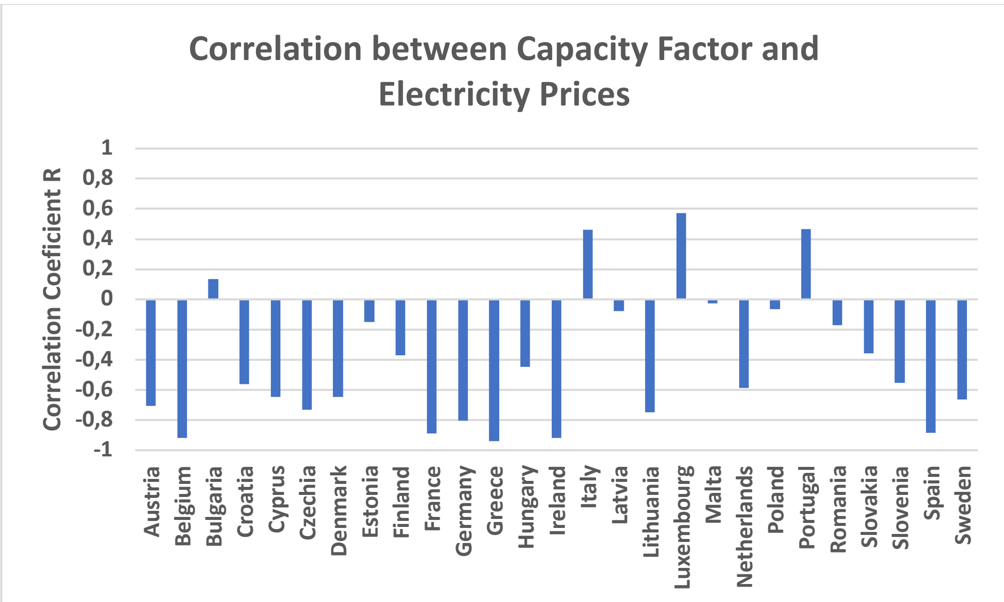

Figure 6.7: Correlation Coefficient R between electricity prices and capacity factor for each country (from 1992 to 2021).

Figure 6.7 demonstrates the relation between the changes in electricity prices and capacity factors for each one of the 27 member states of the European Union for the period 1992-2021. We see that most of the countries follow the same pattern and have in most of the cases R values between -0.60 and -0.90. On the other hand, countries like Bulgaria, Romania and Estonia, where the capacity factors did not follow a clear increasing or decreasing trend throughout all of the studied period and varied at some time, show little to no correlation between the prices and the capacity factors. Finally, Italy and Portugal show a medium positive correlation as the capacity factors in those countries have been constantly dropping since 1990 while at the same time, prices were steady or even slightly reducing.

Overall, can conclude that the decrease of the capacity factors in Europe and by extension the large integration of variable sources (solar and wind) into each country's grid is strongly related to the change in clear electricity prices of the retail market and along with other factors it affects the total amount of money paid for electricity by the domestic consumers.

Chapter 7: Conclusions

7.1 Thesis synopsis and conclusions

The aim of this thesis was to explore many of the aspects of the electricity domain in Europe and based on a multicriteria assessment to investigate the changes in a variety of electricity components throughout a period of 30 years.

Firstly, we did a review of the history and the basic elements of electric power, and the methods of electricity generation. We went through the types of primary energy sources used, and analyzed the advantages and downsides between conventional sources, renewables and nuclear power. Fundamentals of the operation of electricity markets in Europe were also discussed.

We created an energy profile for all 27 of the European Union member states along with a few more countries, by providing information about the historical reforms in their electricity production and demand. We also investigated the composition and the evolution of each country's electricity mix during a period spanning from the early 1990s up to the 2020s and recorded the changes in the total generation capacity.

Following this, we dedicated a chapter exclusively to the use of renewable energy sources for electricity generation. Considering their contribution to the mitigation of the consequences of climate change, we examined how each state moved from an electricity sector based on fossil fuels to an energy system that is characterized by the exponential integration of renewables. The effects of variable renewable sources (wind and solar) on the energy strategy of each country were also discussed.

After evaluating the changes in the basic electricity components, we examined the efficiency of each power source by using the capacity factor as an indicator and concluded that renewable sources and principally the variable ones tend to perform worse than conventional sources due to the fluctuating nature of their resources. We also investigated the impact of the energy policies followed by the European states on the capacity factors and interpreted the overall decrease of the capacity factors as a result of the continent's turn into cleaner and low-carbon electricity by large investments in renewables.

Lastly, we did a brief review of how the economy affects the electricity domain, by examining the impact of basic economic indicators like GDP on electricity components and investigating the effect of Europe's economic growth on the changes in electricity prices.

7.2 Future research perspectives

From the knowledge we gained so far, we detected some issues for further research in the future regarding the electricity domain. Specifically:

- Assessing the effectiveness of the European energy strategies in achieving the low-carbon electricity goals set
- Evaluating the effects of the increase of renewable sources on the stability of the electric grids and the security of the energy supply chain on a national and European level
- Examining the optimization in the management of electric power production and supply, considering the variability of renewable electricity generation and the low large-scale storage ability
- Analysing the performance of the liberalized wholesale and retail electricity markets across Europe and their impact on basic electricity components
- Investigating the impact of the war in Ukraine on electricity components and energy security in Europe

Research on the above can provide valuable conclusions about the transformation of the electricity sector in Europe and can contribute to the design and implementation of more efficient -both in terms of production and in terms of cost- energy policies by each country.

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