University of Piraeus – Department of Informatics
M.Sc. in "Digital Culture, Smart Cities, IoT and Advanced Digital Technologies"

Master Thesis

Thesis Title	**Intelligent Energy Metering Systems, Using Blockchain Technologies and Smart Contracts: A Literature Review** **Ευφυή Συστήματα Μέτρησης Ενέργειας με Χρήση Τεχνολογιών Blockchain και Έξυπνων Συμβολαίων: Μια Βιβλιογραφική Ανασκόπηση**
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Abstract

With the rapid growth of renewable energy resources, the energy trading research has received significant attention during the last years. Blockchain, as a distributed public ledger technology, has been widely adopted to design new energy trading schemes. However, blockchain-based energy trading has numerous challenges, including low efficiency, large transaction costs, and security and privacy concerns. This thesis provides a systematic literature review of the various technical implementation aspects of blockchain-enabled Energy Trading mechanisms in Electrical Power System and in Electric Vehicles sectors respectively. Apart from the two domains of the available blockchain-enabled energy trading mechanisms, different drivers for classifying the literature are being used, such as (a) relevant methodologies used, (b) the implementation maturity of these traceability mechanisms, and (c) the sustainability perspectives (economic, environmental, social). The key findings about the outstanding issues and challenges of current blockchain Energy Trading implementations, as well as areas of interest for future study, are presented. Despite the variety of blockchain-enabled Energy Trading mechanisms, most of the citations published so far, mainly are constrained within unstructured experimentation of blockchain-associated Energy Trading solutions, lacking standardization and benchmarking of the applications proposed, highlighting, at the same time, the clear need for developing and testing real-world solutions, while taking feasibility and cost-related Energy Trading aspects into account.

Keywords

electric vehicles; energy trading; blockchain; Hyperledger fabric; smart contract; electronic wallet; smart cities, Internet of things

Περίληψη

Με την ταχεία ανάπτυξη των ανανεώσιμων πηγών ενέργειας, η έρευνα για το εμπόριο ενέργειας έχει λάβει σημαντική προσοχή τα τελευταία χρόνια. Το Blockchain έχει υιοθετηθεί ευρέως για το σχεδιασμό νέων συστημάτων εμπορίας ενέργειας. Πρόκειται για μια κοινή και κατανεμημένη βάση ψηφιακών δεδομένων που διατηρεί ένα συνεχώς αυξανόμενο αρχείο συναλλαγών με χρονολογική σειρά. Οι συναλλαγές ομαδοποιούνται σε μπλοκ, τα οποία έχουν χρονική σήμανση και είναι κρυπτογραφικά συνδεδεμένα με προηγούμενα μπλοκ για να σχηματίσουν μια αλυσίδα εγγραφών που καθορίζει την αλληλουχία ή αλυσίδα των γεγονότων. Τα blocks της αλυσίδας «τρέχουν» σε ψηφιακά δίκτυα, μεταδίδοντας δεδομένα, αντιγράφοντάς τα από το ένα μέρος στο άλλο. Στον τομέα των κρυπτονομισμάτων, αυτό ισοδυναμεί με την αντιγραφή ψηφιακών νομισμάτων από το ηλεκτρονικό πορτοφόλι ενός χρήστη σε αυτό κάποιου άλλου. Η κύρια πρόκληση έγκειται στο γεγονός ότι το σύστημα πρέπει να διασφαλίσει ότι τα νομίσματα δαπανώνται μόνο μία φορά και ότι δεν υπάρχει διπλή δαπάνη. Αυτό γίνεται: 1) είτε χρησιμοποιώντας ένα κεντρικό σημείο αρχής, που ενεργεί ως έμπιστος ενδιάμεσος μεταξύ των συναλλασσόμενων μερών και αποθηκεύει/εξασφαλίζει την έγκυρη κατάσταση της αλυσίδας και διατηρεί τα αρχεία ενημερωμένα, 2) είτε, από κάθε μέλος του δικτύου blockchain που διατηρεί το δικό του αντίγραφο της αλυσίδας(ή έχει πρόσβαση σε αυτό μέσω ανοιχτού νέφους) και επαληθεύει την εγκυρότητά της. Στην τελευταία περίπτωση, η πρόκληση έγκειται στην εύρεση ενός τρόπου ενοποίησης και συγχρονισμού πολλαπλών αντιγράφων της αλυσίδας. Η διαδικασία επικύρωσης και ενοποίησης της αλυσίδας από τα μέλη του δικτύου γίνεται, συγκρίνοντας τις εκδόσεις τους της αλυσίδας χρησιμοποιώντας ένα κατανεμημένο σύστημα ψηφοφορίας, μέσω του οποίου επιτυγχάνεται συναίνεση για την έγκυρη κατάσταση της. Αυτοί οι μηχανισμοί επικύρωσης είναι γνωστοί ως κατανεμημένοι αλγόριθμοι συναίνεσης. Τα κίνητρα ή οι ανταμοιβές θεωρητικών παιγνίων χρησιμοποιούνται για να διασφαλιστεί η έντιμη συμπεριφορά των κατανεμημένων κόμβων.

Τρεις βασικές ιδέες μπορούν να συνοψιστούν ως απαιτήσεις για μελλοντικά ενεργειακά συστήματα: η απανθρακοποίηση, η αποκέντρωση και η ψηφιοποίηση, με μια στροφή προς την ενδυνάμωση των καταναλωτών. Προς αυτή τη κατεύθυνση, προγραμματιστές blockchain: δημιουργούν συναλλακτικές ψηφιακές πλατφόρμες που μπορούν να είναι πλήρως αποκεντρωμένες και μπορούν να διευκολύνουν το P2P (Peer to Peer) εμπόριο ενέργειας. Αναπτύσσουν τοπικές αγορές ενέργειας και εφαρμογές Internet of Things (IoT) που μπορούν να παίξουν σημαντικό ρόλο στο όραμα του έξυπνου δικτύου (smart grid). Το εμπόριο ενέργειας, ειδικότερα, ως κρίσιμο συστατικό της διαχείρισης ενέργειας, εξελίσσεται από συγκεντρωτικό σε κατανεμημένο τρόπο. Οι πελάτες ενέργειας μπορούν να αγοράσουν ηλεκτρική ενέργεια μόνο από επιχειρήσεις κοινής ωφέλειας στην παραδοσιακή αγορά ενέργειας. Σε ένα έξυπνο δίκτυο, οι χρήστες ενέργειας χρησιμεύουν τόσο ως καταναλωτές όσο και ως προμηθευτές ηλεκτρικής ενέργειας. Η πλεονάζουσα παραγωγή ενέργειας από ανανεώσιμες πηγές μπορεί να ανταλλάσσεται για αμοιβαίο όφελος με την εταιρεία κοινής ωφέλειας και άλλους χρήστες σε περιπτώσεις ελλείμματος τροφοδοσίας. Το μοντέλο δικτύου Peer-to-Peer (P2P) επιτρέπει στην αγορά ενέργειας να λειτουργεί με επίκεντρο τον καταναλωτή και υποστηρίζει τη συμμετοχή των αποκαλούμενων «προμηθευτών».

Μερικές από τις υπάρχουσες εφαρμογές στον ενεργειακό τομέα : Brooklyn microgrid (ΗΠΑ), Sunchain (Γαλλία), Power Ledger (Αυστραλία), Power-ID (Ελβετία), I-NUK (Γαλλία), Tal.Markt (Γερμανία), SolarCoin, NRGCoin (Βέλγιο), DAISEE (Γαλλία), Gruenstromjeton (Γερμανία), Pylon Network Project (Ισπανία), Power-ID. Σε τέτοιες εφαρμογές, κάθε ενεργειακή συναλλαγή καταγράφεται και αποθηκεύεται στο blockchain όλων των υπολογιστών (κόμβων) που αποτελούν το δίκτυό της (π.χ. ένα μικροδίκτυο). Όλοι οι συμμετέχοντες ενημερώνονται για κάθε συναλλαγή σε πραγματικό χρόνο και οι υπολογιστές τους ελέγχουν τους άλλους για την πρόληψη τυχόν απάτης. Οι ταυτότητες των συμμετεχόντων είναι είτε γνωστές (δημόσιο blockchain) είτε ανώνυμες (ιδιωτικό blockchain) ανάλογα με τον τύπο του blockchain. Το αρχείο όλων των συναλλαγών (απόδειξη ύπαρξης) που δημιουργείται, είναι κρίσιμο από νομική και

δικαστική άποψη σε περίπτωση διαφωνίας. Όσον αφορά την ενεργειακή πιστοποίηση και επαλήθευση, το Blockchain μπορεί να επικυρώσει την προέλευση και τον τύπο της ενέργειας ανά πάσα στιγμή με απαράβατο τρόπο (έλεγχος σε πραγματικό χρόνο) και να παράγει ένα αρχείο ιδιοκτησίας για κάθε πιστοποιητικό ανανεώσιμης ενέργειας, να χρησιμοποιηθεί για την καταγραφή, την πιστοποίηση και την επικύρωση των συναλλαγών εκπομπών μεταξύ χρηστών του συστήματος, μια προσέγγιση που εφαρμόζεται στην Κίνα από την IBM και την Energy Blockchain Lab. Με τη δημιουργία ενός συστήματος έξυπνων συμβολαίων (smart contracts) και με την ανάπτυξη αυτόνομων αποκεντρωμένων εφαρμογών (Dapps) που δεν απαιτούν ανθρώπινη αλληλεπίδραση, η επεξεργασία των συναλλαγών μπορεί να αυτοματοποιηθεί και να γίνει ακόμη πιο αποτελεσματική και οικονομικά αποδοτική.

Με την αναμενόμενη ανάπτυξη του IoT τα επόμενα χρόνια, οι τοπικές αρχές θα μπορούν να αποκτούν μια συνεχή διάγνωση όλων των ενεργειακών τους εγκαταστάσεων (μονάδες παραγωγής ενέργειας, έξυπνα δίκτυα κ.λπ.).Ένα blockchain σύστημα σε μόνιμη επικοινωνία με συσκευές IoT που χρησιμοποιεί έξυπνα συμβόλαια και DApps θα μπορούσε θεωρητικά να διαχειριστεί την ενεργειακή υποδομή μιας τοπικής αρχής. Ο συνδυασμός Blockchain και έξυπνων μετρητών μπορεί να χρησιμοποιηθεί για την προσαρμογή ενός συστήματος τιμολόγησης, μειώνοντας τον κίνδυνο δόλιας υπερτιμολόγησης για λογαριασμό προμηθευτών. Τα έξυπνα συμβόλαια θα μπορούσαν να διευκολύνουν την εφαρμογή ενός αυτοματοποιημένου, ευέλικτου μηχανισμού ικανού να αμείβει τους καταναλωτές σε πραγματικό χρόνο και να προσαρμόζει τη ζήτηση όταν είναι απαραίτητο. Χάρη στην ψηφιακή εμπιστοσύνη που παρέχουν τα blockchains, ένα τέτοιο σύστημα θα επέτρεπε στα μέλη του –παραγωγούς και καταναλωτές– να εμπορεύονται ενέργεια με μη αυτόματο ή αυτοματοποιημένο τρόπο (έξυπνα συμβόλαια) σε ένα εναρμονισμένο και ασφαλές πλαίσιο χρησιμοποιώντας εικονικό ή πραγματικό νόμισμα. Οι συμμετέχοντες στο δίκτυο θα επωφεληθούν επίσης από πολύ μικρότερες αποστάσεις μετάδοσης ενέργειας σε σύγκριση με ένα κεντρικό σύστημα, μειώνοντας έτσι τη σπατάλη ενέργειας και το κόστος. Ο μετασχηματισμός των ανανεώσιμων πηγών ενέργειας σε πιστώσεις άνθρακα και η πώλησή τους στην αγορά μπορεί να γίνει πραγματικότητα με τη βοήθεια της τεχνολογίας blockchain και τη χρήση ενός συστήματος έξυπνων συμβολαίων. Τέλος, τα blockchain συστήματα μπορούν να διευκολύνουν την ανάπτυξη της ηλεκτροκίνησης ως υπηρεσίας χάρη στην εφαρμογή ενός απλούστερου και λιγότερο δαπανηρού συστήματος επαναφόρτισης σε σύγκριση με τις υπάρχουσες λύσεις. Τα ηλεκτρικά οχήματα (EV) αποτελούν ένα μεγάλο βήμα προς έναν φιλικό τρόπο μεταφοράς. Ορισμένοι χρήστες παράγουν ηλεκτρισμό χρησιμοποιώντας ηλιακούς συλλέκτες και φορτίζουν τα ηλεκτρικά τους οχήματα. Άλλοι, χρησιμοποιούν σταθμούς φόρτισης και πληρώνουν για τη φόρτιση του οχήματος. Αυτό εγείρει το ζήτημα της εμπιστοσύνης και της διαφάνειας που το Blockchain καλείται να μετριάσει.

Σε αυτή τη διπλωματική παρέχεται: Μια συστηματική έρευνα των διαφόρων διαθέσιμων εφαρμογών συναλλαγών ενέργειας που σχετίζονται με το blockchain. Αυτές οι προσεγγίσεις ταξινομούνται με βάση: 1)τους τομείς δραστηριοποίησης (Έξυπνο Δίκτυο, Ηλ. οχήματα), 2)τις μεθοδολογίες που εφαρμόζονται, 3)την προοπτική βιωσιμότητας, 4)την ωριμότητα της υλοποίησής τους. Η περιγραφική ανάλυση περιλαμβάνει 62 ερευνητικά άρθρα που δημοσιεύθηκαν μεταξύ 2017-2021 και στοχεύει: α) Στη βελτίωση της στατιστικής περιγραφής, ομαδοποίησης και επίδειξης των θεμάτων ενδιαφέροντος της σχετικής βιβλιογραφίας ή των σχέσεών τους (δημοσιεύσεις ανά έτος και τομέα κ.λπ.). β) Στην ενσωμάτωση ανάλυσης των τρεχου-σών τάσεων της έρευνας στον τομέα των μηχανισμών εμπορίας ενέργειας με δυνατότητα blockchain και παρουσίαση των ζητημάτων που έχουν βρεθεί γ) Στη παρουσίαση των διαφόρων ερευνητικών προσεγγίσεων που έχουν χρησιμοποιηθεί μέχρι αυτό το σημείο στην επιστημονική βιβλιογραφία.

Από την ανάλυση των στοιχείων υλοποίησης προκύπτει ότι οι Blockchain δοκιμές περιλάμβαναν: την αξιολόγηση έξυπνων συμβολαίων , δοκιμές API , δοκιμές απόδοσης, δοκιμές κόμβου-αλυσίδας. Οι πιο προηγμένες υλοποιήσεις περιλάμβαναν : τη χρήση αυτοματοποιημένων scripts και δοκιμές απόδοσης, χρησιμοποιώντας εργαλεία όπως Truffle, Ethereum Tester, Populus, ψηφιακές αποκεντρωμένες εφαρμογές (δηλαδή DApps) με ενσωματωμένη διαχείριση ταυτότητας, βελτιωμένες λειτουργίες κλπ. Παρείχαν δείκτες απόδοσης προκειμένου να μετρούν την καθυστέρηση, την απόδοση, την κυκλοφορία δικτύου, τη μνήμη, τη χρήση της CPU και το ποσοστό αποτυχίας των συναλλαγών τους, την ασφάλεια/ το απόρρητο και την επαληθευσιμότητα των δεδομένων εμπορίας ενέργειας, τη δίκαιη κατανομή των πόρων του συστήματος το κόστος λειτουργιών των έξυπνων συμβολαίων (gas). Η πλειοψηφία των εφαρμογών Energy Trading στη βιβλιογραφία χρησιμοποιούν το Ethereum ως την υποκείμενη τεχνολογία blockchain. Η 2η προτιμώμενη τεχνολογία ήταν η Hyperledger. Οι εφαρμογές του blockchain ταξινομήθηκαν επίσης, σύμφωνα με τους αλγόριθμους συναίνεσης που χρησιμοποιούνται. Οι πιο συνηθισμένοι:Proof-of-Work (PoW), Proof-of-Stake (PoS), Practical Byzantine Fault Tolerance (PBFT).

Σχετικά με τα ανοιχτά ζητήματα και τις προκλήσεις των τρεχουσών εφαρμογών blockchain ενεργειακής εμπορίας, τα κυριότερα είναι: 1) η χαμηλή απόδοση και το υψηλό κόστος συναλλαγής, 2) η προστασία απορρήτου και τα θέματα ασφάλειας , 3) η επικοινωνία σε πραγματικό χρόνο μεγάλου όγκου δεδομένων αισθητήρων, 4) η πιθανή άδικη ή κακόβουλη συμπεριφορά από αγοραστές ή πωλητές ενέργειας 5) οι δυσκολίες τιμολόγησης του μοντέλου (πώς πρέπει να τιμολογηθεί σωστά μια συμφωνία για να βοηθήσει τους αγοραστές και τους πωλητές να καταλήξουν γρήγορα σε συμφωνία), 6) η ελαχιστοποίηση του κόστους/ μεγιστοποίηση κέρδους 7) οι απαιτήσεις σε μεγάλο αποτύπωμα άνθρακα. Επιπλέον , όσον αφορά τις πειραματικές δοκιμές, οι περισσότερες αναφορές στη βιβλιογραφία προσομοιώνουν τις σχετικές λειτουργίες μόνο σε επίπεδο πλατφόρμας blockchain χωρίς να τις συνδέουν με το πραγματικό φυσικό σύστημα. Οι τεχνολογικές προκλήσεις που προκύπτουν αφορούν τους τομείς: της απόδοσης, του χρόνου συναλλαγής, της επεκτασιμότητας, των κατανεμημένων αλγόριθμων συναίνεσης προκειμένου να επιτρέπουν την παράλληλη επεξεργασία, την ανάπτυξη πιο αποτελεσματικών και ασφαλών έξυπνων συμβολαίων, τη διαχείριση δεδομένων με στόχο την ελαχιστοποίηση της αποθήκευσης δεδομένων στην αλυσίδα (π.χ. αποκεντρωμένη αποθήκευση δεδομένων στο cloud), τους κίνδυνους για το απόρρητο και την ασφάλεια (τρωτά κυρίως τα ψηφιακά πορτοφόλια ή τα έξυπνα συμβόλαια). Παρατηρείται επιπλέον έλλειψη τυποποιημένων σημείων αναφοράς (benchmarking), για τη συγκριτική αξιολόγηση των εφαρμογών. Επίσης, η προοπτική της βιωσιμότητας υπονοήθηκε σε όλες τις επιλεγμένες εργασίες, αλλά δεν αναφέρθηκε διεξοδικά. Δεδομένων των τεράστιων ενεργειακών απαιτήσεων των σημερινών δικτύων blockchain, οι ανησυχίες που σχετίζονται με το περιβάλλον είναι σημαντικές. Η εξόρυξη κρυπτονομισμάτων απαιτεί υπολογιστές υψηλής απόδοσης . Το γεγονός αυτό οδηγεί σε υψηλό κόστος ανάπτυξης. Τα blockchain μπορεί να πραγματοποιήσουν σημαντική εξοικονόμηση κόστους παρακάμπτοντας τους μεσάζοντες, ωστόσο, απαιτούν δαπανηρή νέα υποδομή, προσαρμοσμένο εξοπλισμό και κόστη συντήρησης. Όλα τα παραπάνω μπορεί να κάνουν τους επενδυτές να πιστεύουν ότι μπορεί να μην έχουν το ανταγωνιστικό πλεονέκτημα έναντι των ήδη υπαρχουσών λύσεων σε καθιερωμένες αγορές. Δεδομένου ότι τα δίκτυα blockchain δεν μπορούν να εγγυηθούν την ακρίβεια των δεδομένων που δεν δημιουργήθηκαν εγγενώς στην αλυσίδα (όπως πληροφορίες που προέρχονται από συσκευές IoT), η μελλοντική έρευνα θα πρέπει να επικεντρωθεί σε τρόπους διασφάλισης της πηγής των παραγόμενων πληροφοριών και της ακρίβειας και ακεραιότητας των δεδομένων. Σχετικά με το ρυθμιστικό πλαίσιο θα απαιτηθούν νέοι τύποι συμβάσεων για την περιγραφή συμφωνιών μεταξύ προμηθευτών και καταναλωτών, ειδικά όταν οι αντισυμβαλλόμενοι κάνουν χρήση του δημόσιου δικτύου. Αυτό συνεπάγεται την ανάγκη για νέα και δυνητικά πιο ευέλικτα τιμολόγια ηλεκτρικής ενέργειας, τα οποία επί του παρόντος υπόκεινται σε αυστηρές ρυθμίσεις. Επιπλέον, οι ρυθμιστικές αρχές είναι υπεύθυνες για τον καθορισμό των κανόνων προστασίας των δεδομένων των καταναλωτών, όπως η πολιτική GDPR της ΕΕ για τα δεδομένα των καταναλωτών. Οι χρήστες του συστήματος blockchain θα πρέπει να συμμορφώνονται με τις υποχρεώσεις τους, αλλά ταυτόχρονα, οι ευαίσθητες πληροφορίες των καταναλωτών πρέπει να παραμένουν εμπιστευτικές. Τέλος, σχετικά με τη τυποποίηση και πιστοποίηση της διαδικασίας : πρέπει να αναπτυχθούν πρότυπα και πρωτόκολλα για τις αρχιτεκτονικές blockchain για να επιτρέπουν τη διαλειτουργικότητα μεταξύ τεχνολογικών λύσεων.

Συμπερασματικά, ο μέχρι τώρα αδόμητος πειραματισμός των λύσεων εμπορίας ενέργειας που σχετίζονται με blockchain για λογαριασμό των ερευνητών, πρέπει να προσανατολιστεί προς την ανάπτυξη δοκιμαστικών εφαρμογών στην πραγματική ζωή, ιδίως λαμβάνοντας υπόψη την ικανότητά τους να δημιουργούν προστιθέμενη αξία.

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1. Introduction

1.1 BACKGROUND

The Internet has revolutionized the way people perceive the world and is now an integral part of their daily lives. Its underlying technologies are continually changing, while new ones are being developed. The dominant client-server architecture, on which the bulk of internet applications and services are based, is a feature of the internet that has remained stable for a long time. This is expected to change greatly due to the emerging technological trends, including blockchain and Internet of Things, that may give the internet a more decentralized character.

The blockchain technology was originally created for the operation of the Bitcoin cryptocurrency, a distributed electronic cash payment system that uses peer-to-peer (P2P) communication between anonymous and unknown Internet users. However the scope of blockchain is constantly evolving and has expanded to various fields. Blockchain is a digitally distributed public ledger, in which transactions and agreements are recorded seamlessly and it is supported by a network of peer nodes. More crucially, blockchain enables peer-to-peer (P2P) networks to execute smart contracts automatically [62]. In addition to its cryptocurrency applications, it can be a pillar for the design and operation of a variety of decentralized applications (DApps), which are based on a distributed network of peer nodes rather than on an organization's servers, making use of cryptocurrencies or tokens and storing outputs in public ledgers.

The Internet of Things, which consists of a plethora of gadgets and sensors with limited computing resources and vulnerable to security attacks, may benefit from the advantages of blockchain technologies, in terms of product traceability, network performance, resource distribution, security and privacy. In this thesis, we focus on the existing literature regarding Blockchain technologies, with a special emphasis on Energy Trading applications.

1.2 BLOCKCHAIN TECHNOLOGY: DEFINITION AND OUTLINE OF FUNDAMENTAL PRINCIPLES

A blockchain is a digital data structure, or more specifically a shared and distributed database that holds a continuously growing log of transactions in chronological order. The data structure is a ledger that may contain digital transactions, data records and executables. Transactions are grouped into blocks, which are time-stamped and cryptographically linked to previous blocks to form a chain of records that determines the sequencing order of events or the ‘blockchain’.[63] Blockchains run on digital networks, and transmit data, by copying them from one place to the other; in the cryptocurrency domain this is equivalent to copying digital coins from one user's electronic wallet to another's. The main challenge lays in the fact that the system needs to ensure that coins are only spent once and there is no double-spending. This is achieved 1) either by using a central point of authority, that acts as the trusted intermediary between transacting parties, stores/secures the valid state of the ledger and keeps the records up to date, or 2) in contrast to centralised systems, by each member of the blockchain network by holding its own copy of the ledger (or accessing it through the open cloud) and by verifying their validity. In the latter case, the challenge lies in finding a way to consolidate and synchronise multiple copies of the ledger. In general, the validation and ledger consolidation process lies on network members comparing their versions of the ledger using a distributed voting [64] system, through which consensus on the valid state of the ledger is reached. These validation mechanisms are known as distributed consensus algorithms. Game-theoretic incentives or rewards may be used to ensure the honest behaviour of the distributed nodes [65]. Central management may not be feasible or desirable in some cases, as it incurs intermediary costs and requires network users to trust a third party to operate the system [66]. Due to a single point of failure, centralized systems have substantial disadvantages, making them more vulnerable to both technological failures and malicious attacks [67].

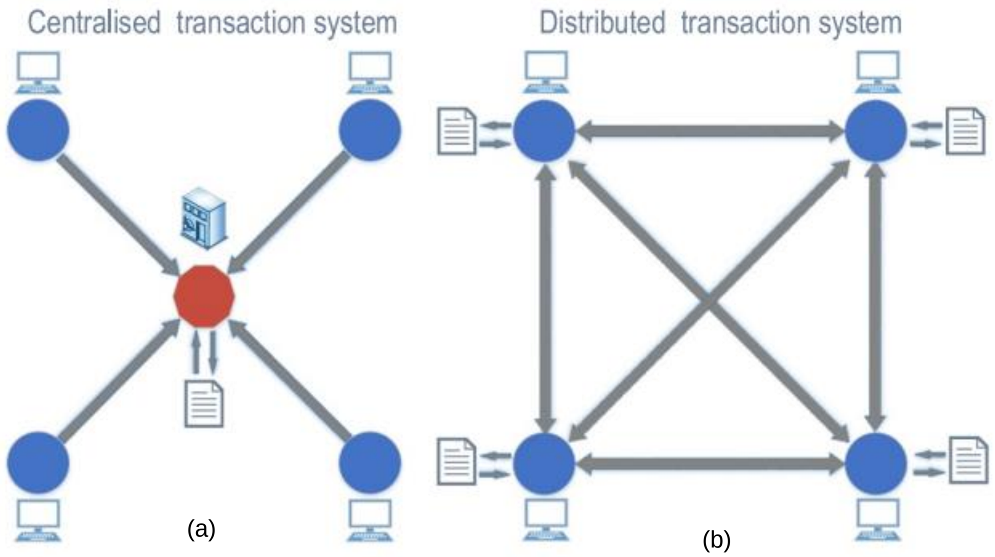


Figure 1. Centralised and distributed transactional platforms: a) a single trusted authority manages the ledger, b) every member holds a copy of the ledger. Reprinted from "Blockchain technology in the energy sector: A systematic review of challenges and opportunities", by Merlinda Andoni, Valentin Robu, David Flynn, Simone Abram, Dale Geach, David Jenkins, Peter McCallum, Andrew Peacock, Renewable and Sustainable Energy Reviews, Volume 100, Issue 8, pp. 143-174, Feb. 2019. Copyright (2019) by title of publisher.

1.3 PEER-TO-PEER ENERGY TRADING

Blockchain in Energy Trading Systems

Along with use cases in various sectors, the potential of blockchains in the energy business has only recently begun to be realized, as evidenced by the growing number of startups, pilots, trials, and research initiatives. Several energy utility companies have taken interest in exploring the potential benefits of distributed ledger technologies (DLT), as an enabling technology for low-carbon transition and sustainability [66]. Furthermore, because blockchains are digital assets that can be exchanged interoperably, they have the potential to dramatically alter energy-related products and commodities. Early research initiatives and startups indicate that blockchain technology could potentially provide solutions to some of the challenges faced by the energy industry. Three essential ideas can be summarized as requirements for future energy systems: decarbonisation, decentralisation, and digitization, with a parallel shift toward consumer empowerment. Early blockchain developers are establishing transactional digital platforms that can be completely decentralised and can facilitate P2P energy trading. They are developing local energy marketplaces and Internet of Things (IoT) applications that can play a significant role in the vision of the smart grid [48].

New models, technologies, and adaptable solutions for intelligent energy management are being created in smart grids to support the most efficient energy and power flow strategies. Energy trading, in particular, as a critical component of energy management, is evolving from a centralized to a distributed manner. In the traditional energy market, energy customers can only buy electricity from power utilities. In a smart grid, energy users serve as both consumers and suppliers of electricity. Excess renewable energy generation can be traded for mutual benefit with the utility and other users in the deficit of power supplies.

Many studies have attempted to integrate blockchain technology into energy trading, bringing up a unique and promising area of research [68][69]. Some academics researched the applicability of distributed systems to the energy market before formally attempting to combine blockchain with the energy trading model. It is proven that, Peer-to-Peer (P2P) network model enables the energy market to operate in a consumer-centered manner and supports the participation of the so-called “prosumers”, which has greatly improved the flexibility of the traditional mode of energy market [70][71].

Brooklyn microgrid(1) (USA), Sunchain(2) (France), Power Ledger(3) (Australia), Power-ID(4) (Switzerland), I-NUK(5) (France), Tal.Markt(6) (Germany), SolarCoin(7), NRGCoin(8) (Belgium), DAISEE(9) (France), Gruenstromjeton(10) (Germany), Pylon Network Project(11) (Spain), Power-ID(12) are only some of the existing applications in the energy field [56].

In such applications, each energy transaction is recorded and stored by the blockchain on all the computers (nodes) which form its network (e.g. a microgrid). All the participants are informed of each transaction in real time and their computers control the others to prevent fraud. By establishing a smart contract system and, in the future, by deploying autonomous decentralised applications (Dapps) that do not require any human interaction, **transaction processing** can be automated and made even more efficient and cost-effective [72]. Examples: Sunchain, Brooklyn Microgrid, Tal.Markt, Power-ID.

While Blockchain technology is used to record and store all energy flows and transactions in a distributed and secured way, it can also be used to **document** at any given point in time which users have energy, how much energy they have produced, sold or bought and how their energy assets/portfolio has evolved over time **(asset management)**. All this is carried out transparently and every stakeholder – energy service companies (ESCOs), distribution system operators (DSOs), transmission system operators (TSOs), energy community organisations, local authorities through their energy departments– has access to this indelible and forgery-proof data at any time. As a result, a record of all transactions (proof of existence) may be generated, which is critical from a legal and judicial standpoint in the event of a dispute. The participants' identities are either known (public blockchain) or anonymous (private blockchain) depending on the type of blockchain. Examples: Gruenstromjeton, Sunchain, I-NUK

In terms of **energy certification and verification**, Blockchain can validate the provenance and type of energy at any moment in a tamperproof manner (real-time auditing) and produce a record of ownership for each renewable energy certificate thanks to its documentation capacity. It can also be used to record, certify and validate emission trading between players in the system, an approach that is being implemented in China by IBM and the Energy Blockchain Lab. Examples: Sunchain, Pylon Network Project, I-NUK

Blockchain can also be utilized as a **real-time monitoring and control system** of the energy use by local authorities or citizens via a smart meter, as well as to facilitate the exchange of data between various players in an energy system. With the expected development of IoT over the next few years, local authorities will be able to acquire an ongoing diagnosis of all their energy facilities (energy producing units, smart grids, etc.). A blockchain in permanent communication with these IoT devices which uses smart contracts and DApps could in theory manage a local authority’s energy infrastructure, without requiring direct human intervention [73]. Examples: DAISEE, Pylon Network Project, Gruenstromjeton

By lowering the danger of fraudulent overbilling by the suppliers, the combination of Blockchain and Smart meters can be used in the adaption of an **invoicing system**. Examples: Gruenstromjeton, Power-ID.

(1) www.brooklynmicrogrid.com
(2) www.sunchain.fr
(3) www.powerledger.io/
(4) www.im.ethz.ch/people/sschopfer.hml
(5) www.inuk.co
(6) www.wsw-talmarkt.de/#/home
(7) www.solarcoin.org
(8) www.nrgcoin.org
(9) www.daisee.org

(10) www.energieagentur.nrw/eanrw/sev_gruenstromjetons

Moreover, using either a real or a virtual currency, blockchain can be utilized to shake up the energy sector's renumeration system (like Bitcoin or Ether). Smart contracts could facilitate the implementation of an automated, flexible mechanism capable of **renumerating prosumers** in real time and of adjusting demand when necessary (demand response). This mechanism would also make energy micro-payments possible with virtually zero overhead costs and at very short time intervals (every 15 minutes for instance), since the presence of a traditional intermediary like an energy service or payment company is not needed. Examples: SolarCoin, Gruenstromjeton, NRGCoin, Brooklyn Microgrid

Another possible application would be to use blockchain technology in a **local or regional on-line energy marketplace**. The local authority would then take on a new role, that of intermediary, by serving as a matchmaker and coordinator between local energy producers and citizens. Examples: Tal.Markt, Power-ID

Blockchains could also be used to organise **peer-to-peer** t**ransactions** and collective self-consumption **in a decentralised system**. Thanks to the digital trust provided by blockchains, such a system would enable its members – producers and consumers alike – to trade energy in a manual or automated way (smart contracts) within a harmonised and secured framework utilizing a virtual or a real currency. Smart contracts would regulate energy consumption and production in real time. In comparison to a centralised system, network participants would benefit from substantially shorter energy transmission distances and lower energy waste and expenses (e.g. marginal cost).). Smart contracts would ensure system stability by independently handling energy storage, the balancing market and the balance between energy supply and demand. Examples: NRGcoin, Power-ID, Brooklyn microgrid

With the use of blockchain technology and a smart contract system, it is possible to tranform renewable energy into carbon credits and sell them on the market, or to **offset a carbon-intensive activity**. This can be made much more practical and easier to execute and monetise (in real or virtual currency) with blockchain technology. Example: I-NUK

Finally, compared to existing systems, blockchains can aid the growth of **e-mobility as a service** by implementing a simpler and less expensive recharging mechanism. They could also "uberise" and facilitate direct car hiring between owners thanks to the use of innovative payment systems like pay-per-use. Example: Sunchain

Other examples of current experiments applying blockchain technology to the energy sector are the following [56]:

- The city of Riga, plans to use blockchain's security to entice more private investors to invest in a renewable fund that will be used to fund the rehabilitation of private structures.
- The confluence district in Lyon will be the pilot site for a blockchain (deployed by Bouygues Immobilier) designed to collectively control a smart electricity distribution network and ensure that the energy produced is used on the spot. (13)
- The city of Copenhagen and the Danish island of SAMSØ, cooperate with the Blockchain Labs for Open Collaboration start-up to test blockchain technology in their areas (implementing a decentralised network and connecting existing renewable asset infrastructure to the blockchain). (14)
- Wien Energie, the energy department of the city of Vienna, has launched a blockchain pilot project to facilitate energy trading on the wholesale market. (15)
- The industrial services of six Swiss cities, including Geneva, Lausanne and Bern, use the blockchain infrastructure of the Energy Web Foundation, an organisation (members of which include companies Shell and Engie) to identify practical blockchain applications and implement them through pilot projects.(16)

(13) www.bouygues-immobilier-corporate.com/news-room/bouygues-immobilier-sassocie-stratumn-et- energisme-pourdeployer-une-blockchain-pour-smart
(14) www.un-bloc.com/project/energy
(15) www.coindesk.com/wien-energie-preparing-blockchain-world-energy-markets
(16) www.ictjournal.ch/news/2017-12-01/les-services-industriels-de-six-villes-suisses-cooperent-dans-la-blockchain

- The WEPOWER start-up, based in Gibraltar and supported by the EU CIVITAS initiative, aims to create a blockchain platform to facilitate green energy trading using a kind of cryptocurrency (tokens). (17)
- OURPOWER, the Scottish not-for-profit energy supplier will be involved in a pilot project (CEDISON) financed by the British government and aimed at exploring blockchain potential in rural and urban decentralised energy networks. (18)

1.4 BLOCKCHAIN FOR ELECTRIC VEHICLES ENERGY TRADING

As the world is moving rapidly from carbon-producing vehicles to green transportation systems, electric vehicles (EV) are a big step towards a friendly mode of transport. Some users generate electricity using solar panels and charge their electric vehicles. In contrast, some use charging stations, and they pay for vehicle charging. This raises the question of trust and transparency. Blockchain is a modern-day solution that mitigates trust and privacy issues.

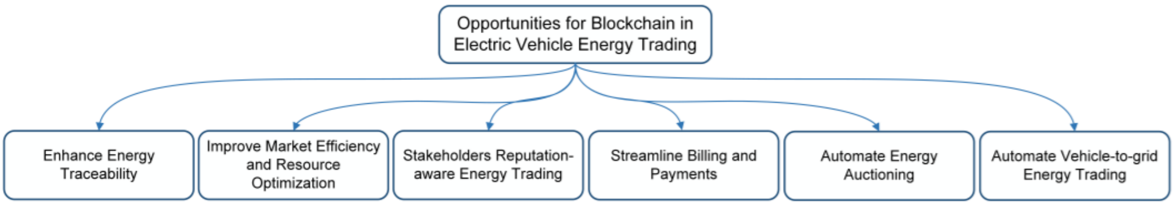


Figure 2. An overview of the potential opportunities for blockchain technology in electric vehicles energy trading. Reprinted from "Blockchain for Electric Vehicles Energy Trading: Requirements, Opportunities, and Challenges", by Nasser Al-Saif, Raja Wasim Ahmad, Khaled Salah, Ibrar Yaqoob, Raja Jayaraman, Mohammed Omar, IEEE TechRxiv 2021. Copyright (2021) by title of publisher.

As depicted in figure 2, a peer-to-peer energy trading and charging payment system for electric vehicles based on blockchain technology is proposed in [57], in which users with excess electricity can sell it to charging stations via smart contracts. Electric vehicle users can pay the charging bills through electronic wallets. The payment will be automatically deducted from their wallet according to the charging time and amount through the smart contract. The electric vehicle's automatic-payment system utilizes the open-source platform Hyperledger fabric. The suggested approach can eliminate human involvement while increasing trust, transparency, and privacy among EV participants.

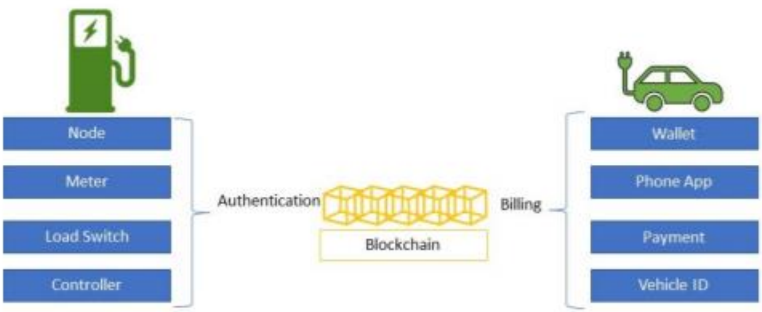


Figure 3. Charging and EV data. Reprinted from "Blockchain-Based Peer-to-Peer Energy Trading and Charging Payment System for Electric Vehicles," by Prince Waqas Khan and Yung-Cheol Byun, 2021, Sustainability, 13, 7962, page 6. Copyright (2021) by title of publisher.

(17) www.wepower.network
(18) www.our-power.co.uk

Figure 3 depicts a graphic representation of the charging and EV data integration scenario. A meter, load switch, controller, and unique node information storage are all included in the charging stations, and they are all authenticated using blockchain. At the same time, the owner of the electric vehicle has a digital wallet with which to make payments. A phone application allows users to examine and check their payment details. The process of blockchain starts with the initialization of a transaction by any peer or node of the chain. The transactions are then combined in a block. The consensus algorithm verifies that block. After the verification of the block, the block becomes part of an immutable chain, in which every transaction is time-stamped, and nobody can tamper with these transactions.

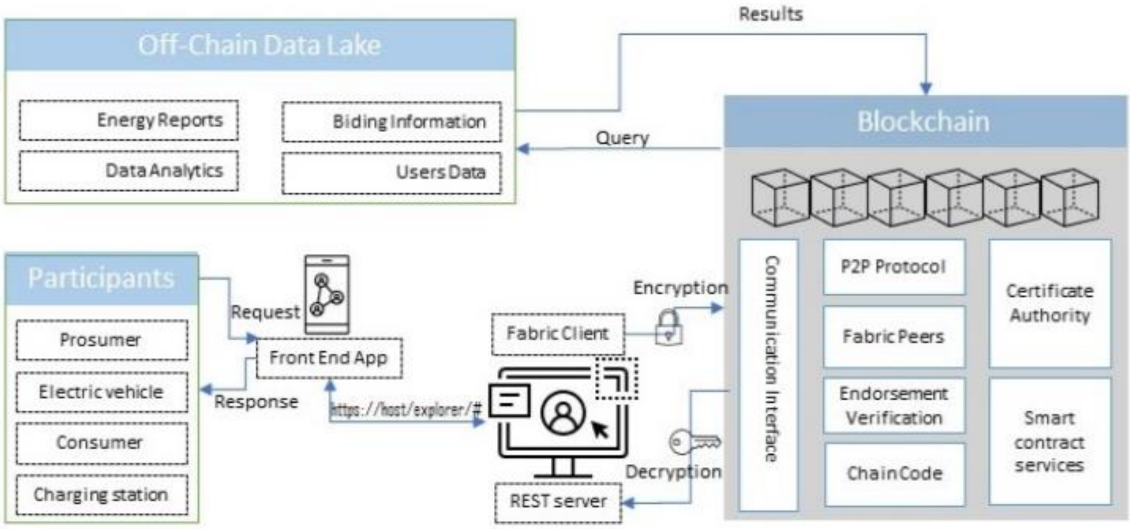


Figure 4. Block diagram of the proposed blockchain-based P2P system. Reprinted from "Blockchain-Based Peer-to-Peer Energy Trading and Charging Payment System for Electric Vehicles," by Prince Waqas Khan and Yung-Cheol Byun, 2021, Sustainability, 13, 7962, page 7. Copyright (2021) by title of publisher.

Participants in the proposed system can communicate with the blockchain via Representational State Transfer (REST) services. The Fabric client facilitates the interaction of blockchain and the REST Application Programming Interface (APIs). Participants (prosumers, consumers, and charging station operators) can access the blockchain through a graphical user interface (GUI)-based application.

- The prosumers produce electricity using renewable energy sources and sell excessive energy after their usage. The prosumers can sell energy and receive payment through the proposed blockchain-based mechanism.
- To purchase electricity, the consumers can bid or contact the seller or the prosumer. The transactions do not require the use of any intermediaries. The blockchain provides a trusted environment to trade.
- The charging station operators can get electricity both from smart grids and from prosumers.

First, the participants need to connect through the Internet, and then they can access the application through a mobile or a computer. The different blockchain components work according to the predefined rules. Every node contains a copy of the chaincode, which is the set of rules which automatically execute according to these predefined rules (smart contract). Finally, the certificate authority issues the certificate to the new nodes. Since this is a permissioned blockchain, no one can join this blockchain without having a certificate. Reports and analytical data are stored in the off-chain data lake.

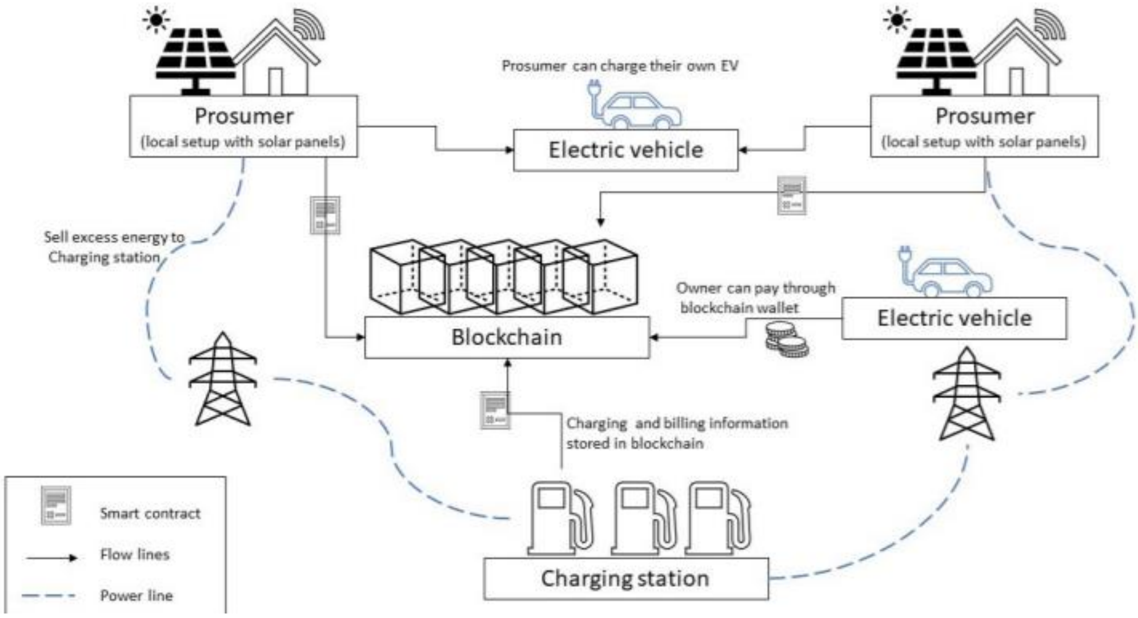


Figure 5. Block diagram of a blockchain-based P2P system

Blockchain technologies have been explored by a large number of companies for their use in EV applications. Electric vehicles and e-mobility are a natural application for blockchains.

- MotionWerk is a German-based startup that specializes in providing energy charging platforms for electric vehicles
- Share&Charge is an application that provides a P2P service that allows electric vehicles and charging station owners to securely and reliably trade energy without relying on a centralized third-party service.
- eMotorWerks is an electric vehicle charging company that has recently created a P2P charging platform in California
- Power Ledger provides a platform that enables tracking and trading of energy using blockchain technology. This company was developed by an Australia-based agency and enables P2P solar energy trading between electric vehicles in an efficient, fast, and transparent way [58]. It also enables Vehicle-to-Grid (V2G) and Grid-to-Vehicle (G2V) energy trading and offers flexibility to the users to sell surplus energy at suitable rates.

1.5 MOTIVATION AND CONTRIBUTION

The blockchain-related energy trading research has received significant attention during the last years. A plethora of review papers exist in the literature concerning blockchain-enabled energy trading systems. From a technical perspective, the authors in [1] provide an overview of a cloud service platform for integrated energy market using the Digital Currency Electronic Payment (DCEP) to user interface characteristics of blockchain-enabled energy trading system. In [10], is proposed a blockchain-based decentralized energy flexibility market enabling small-scale prosumers to trade in a peer-to-peer fashion their flexibility in terms of load modulation concerning the baseline energy profiles. An energy flexibility token for digitizing the flexibility of prosumers, allowing to be traded on the market is being defined, self-enforcing smart contracts, for decentralizing market operation functions are being developed, while algorithms for flexibility bids and offers matching are being defined, based on greedy heuristic and on bipartite graphs. In Table 1 we present the various features and scope of similar review papers and the scope/purpose of the thesis.

A systematic survey of the various technical implementation aspects of blockchain- enabled energy trading mechanisms and their sustainability perspective, are provided in this thesis, with a special focus on the maturity of their implementation status. More specifically, different drivers for classifying the selected literature are being implemented, such as (a) the various domains of the available blockchain-enabled energy trading mechanisms and relevant methodologies applied; (b) the implementation maturity of these mechanisms along with technical implementation details; and (c) the sustainability perspective (economic, environmental, social) prevalent to these implementations. Therefore, the main contributions of this thesis are the following:

A/A	Domain	Objective
[5]	Electric Vehicles in Smart Cities	A secure and efficient V2G energy trading framework is being proposed, by exploring blockchain, contract theory, and edge computing.
[10]	Connected EVs	A Decentralized Electricity Trading Framework (DETF) is depicted, between Connected Electric Vehicles (CEVs) in parking lots based on a consortium blockchain, Machine Learning, and Game theoretic based model.
[11]	Pricing scheme for Peer-to-Peer energy trading based on PoS BC	Methods, benefits and challenges of public blockchain-based pricing sheme for energy trading are presented and analyzed.
[13]	SynergyChain	A blockchain-assisted adaptive model for improving the scalability and decentralization of the prosumer grouping mechanism in the context of peer-to-peer energy trading is proposed.

Table 1. List of blockchain-related energy trading review papers

1. A detailed taxonomy of the available blockchain-related energy trading implementations is being presented. These implementation approaches are being classified based on the various domains, the methodologies applied, and their sustainability perspective.

2. Based on the above classification pattern, their technical characteristics and implementation maturity details are being identified (blockchain platforms used, relevant DApps, etc.).

3. Issues prevalent to blockchain- related energy trading implementations, as well as research gaps and open issues that remain unaddressed, are being outlined.

The rest of the thesis is being organized as follows. In Section 2 the methodology adopted for conducting the systematic review is being presented. In Section 3, the classification of the available literature is demonstrated. In section 4, the key findings various challenges and open issues of blockchain- related energy trading implementations are highlighted, as arisen from the research. The thesi ends with some concluding remarks in section 5.

2. Methodology

This section outlines the methodology adopted for carrying out the systematic literature review of this thesis. The review protocol consists of four steps (and three phases respectively):

1) Determine the scope of the review
2) Search the various databases
3) Perform content analysis,
4) Amalgamate and summarize the results of the survey.

2.1. DEFINITION OF THE SCOPE OF THE REVIEW

The goal of any systematic review is to amalgamate the available literature in a systematic, transparent, and reproducible manner, thus contributing in the creation process of policy and decision-making [74]. The systematic literature review of this thesis is based on standardized processes for scanning, analyzing, and synthesizing the available literature within the specific given domain of blockchain-enabled energy trading implementations.

The overall approach is based on certain research key points relevant to blockchain-enabled energy trading implementations, which are clearly connected with the objectives of the thesis. According to these research key axes, a thorough analysis of the available literature is being carried, in order to evaluate the technical deployment aspects of energy trading Blockchain applications, as well as, to examine the maturity of these implementations. The major research key axes are summarized in Table 2.

Table 2. Research key axes and objectives of the survey

Key Axes	Objectives
Domain-specific aspects of the maturity of the blockchain-enabled Energy Trading implementations	To provide a mapping of the available blockchain-related enabled Energy Trading implementation frameworks and their characteristics (methodologies, product classification etc).
State of the art in terms of maturity implementation of the available blockchain Energy Trading mechan-isms	To provide a classification of the technical characteristics of the available blockchain-specific Energy Trading implementations (implementation maturity, blockchain platforms, consensus mechanisms used etc.).
Sustainability perspectives within these blockchain-enabled Energy Trading implementations	To screen how the available blockchain-related Energy Trading frameworks satisfies the threesome angles of sustainability (economic, environmental, social).
Main challenges and limitations for blockchain-enabled Energy Trading implementations	To classify current challenges prevalent to the blockchain-related Energy Trading implementation frameworks and to determine areas of future research work.

2.2. SEARCH STRATEGY

In order for the literal review to be concentrated and presented in the master thesis, we mainly used Scopus, as well as some papers from Google Scholar. The methodology pattern that was implemented follows the steps described below:

1. A predefined set of terms was used for searching within the titles, abstracts and keywords of all the available Scopus papers. The terms included the Key word selection "TITLE-ABS-KEY: “Energy Trading”, “Blockchain” and “Smart Contract”.
2. Time range selection: Citations from 2017 up to the present were used for our bibliographic research.

3. The acceptability of the retrieved literature (in total, 257 papers), was further examined, based on a set of inclusion/exclusion criteria. Advanced search criteria: "Conference proceedings" category was excluded from source type, whilst the subject areas were limited to the fields of "Engineering", "Computer Science", "Energy", "Business Management & Accounting".
4. Language selection: The fragmented literature, was further limited to exclusively English written documents.

Thus, from the initial 257 document results, 62 citations ultimately remained, from which 40 citations were utilized, since the other 12 were containing literature review approach, regarding the state of the art in Energy Trading blockchain-based implementations. The majority of the citations selected were articles (>75%), following by reviews, book chapters and Conference papers/reviews.

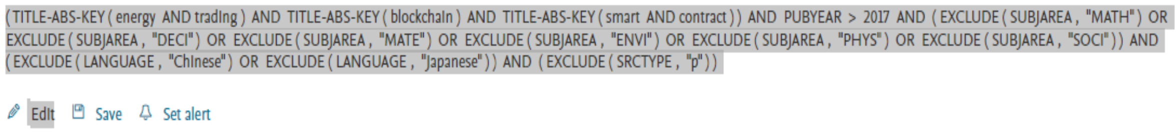


Figure 6. Filters applied, to excluded citations.

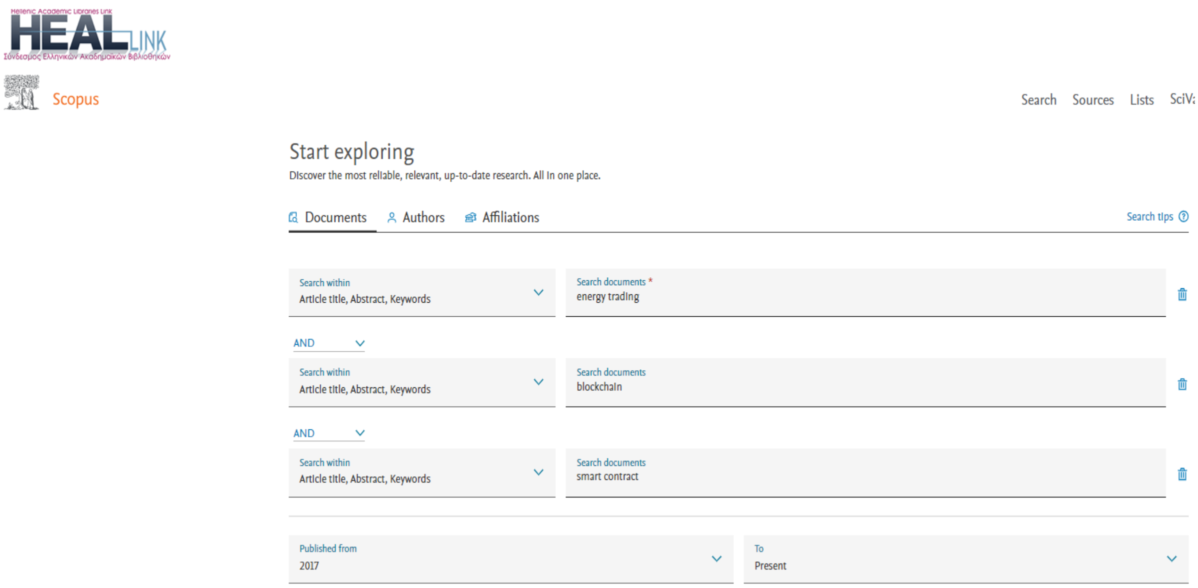


Figure 7. Scopus environment-Literature search

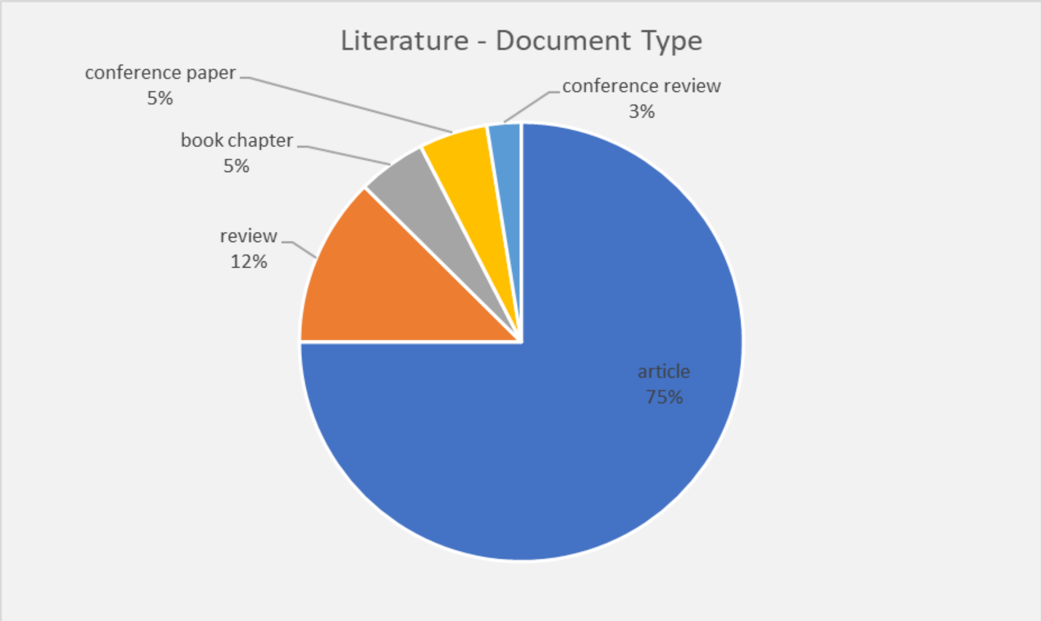


Figure 8. Bibliographic source distribution.

2.3. CONTENT ANALYSIS

The thematic content analysis facilitates the descriptive screening of the qualitative data and aids researchers to identify and decode patterns of meaning (or "themes") within the qualitative data [75,76]. A thematic content analysis approach was adopted here, for developing research areas and common themes from the relevant literature.

2.4. AMALGAMATION AND REPORTING

In order to summarize and synthesize the extracted data, multiple categorizations of the available blockchain-enabled energy trading applications, were utilized, based on:

a) the specific energy trading domain and product/service in which they are applied,

b) relevant methodologies used,

c) the sustainability perspective covered,

d) their technical features.

Furthermore, a narrative synthesis to classify and unify the extracted data was used as a qualitative analysis method. The narrative synthesis combines the results from multiple studies in a qualitative manner, by concentrating on the way studies that address a different aspect of the same phenomenon can be narratively compiled and built up to provide a map of that phenomenon.

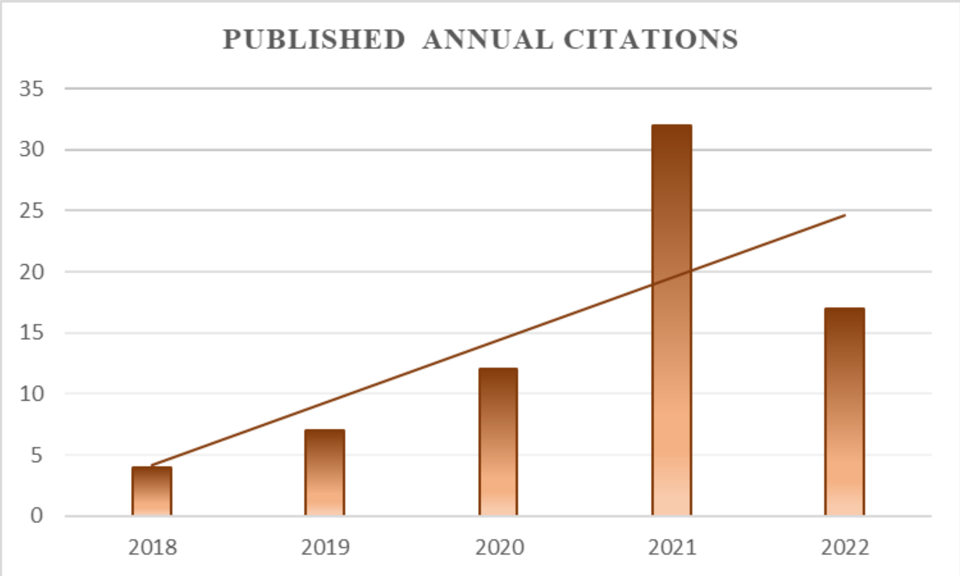


Figure 9. Distribution of citations per year

2.5. BIBLIOGRAPHIC ANALYSIS

A descriptive analysis of the selected papers included in the thesis follows. The descriptive analysis includes 40 research articles published between 2017-2021 (as of January). The proposed descriptive analysis aims at:

1. Improving the statistical description, clustering, and demonstration of the relevant literature's subjects of interest or their relationships (publications per year and domain etc.).

2. Incorporating an analysis of current research trends in the field of blockchain-enabled energy trading mechanisms and featuring the issues that have been found, thus, enabling the taxonomy described in Section 3.

3. Presenting the various research approaches used up to this point in the scientific literature, regarding the rapid development of blockchain-enabled energy trading mechanisms and their implementation status.

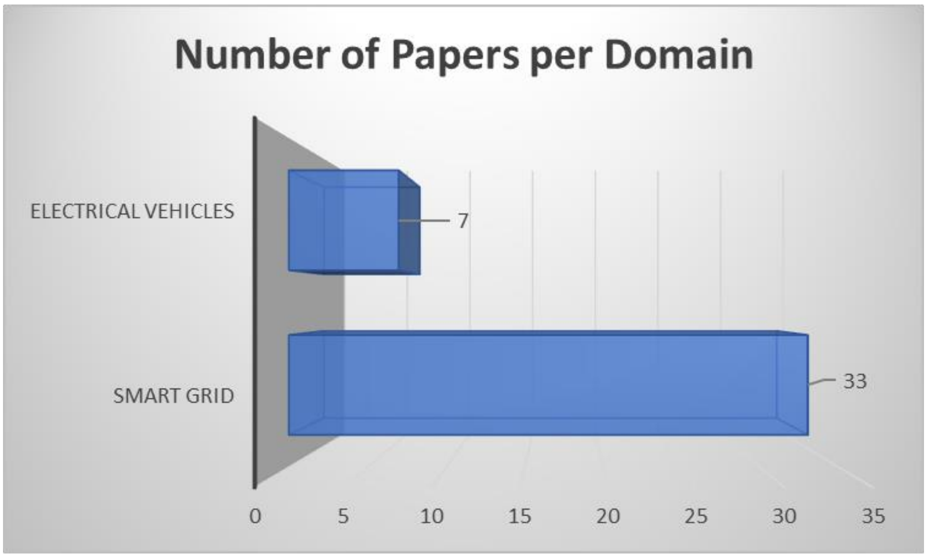


Figure 10. Domains of blockchain-specific Energy trading implementations

The apportionment of publications based on time is depicted in Figure 9, where a year-by-year analysis of the selected papers is depicted. It is worth noticing that the majority of the publications lies in 2021 with 32 citations versus 11 citations that were published in 2020. In the last two years, there has been an explosion of blockchain research in the field of energy trading frameworks. Until the end of 2019, only 7 papers described blockchain-specific energy trading implementations. Note that the final number of papers appearing in Scopus for 2022 will be eventually higher (due to listing/indexing lag). Therefore, over the last couple of years, research in blockchain and energy trading has slowly but steadily increased. Figure 10 shows the domain-specific distribution of the 40 peer-reviewed papers included in the analysis. It is worth noting that (7) citations refer to the use of blockchain in implementations in the electrical vehicles industry, while the rest (33) in smart grid implementations proposing a decentralized energy management system. This immense research focus on smart grid applications with renewable energy resources can be explained as a promising solution effort to alleviate energy crisis and environmental pollution problems. Table 3 depicts the peer-reviewed journals in which the selected papers were published. It is worth noting that 15 out of the 40 papers (37,5%) were published in IEEE in the fields of Transactions on Industrial Informatics, Transactions on Intelligent Transportation Systems, Transactions on Smart Grid, Internet of Things Open Access, International Journal of Emerging Electric Power Systems, Transactions on Industry Applications, Transactions on Green Communications & Networking etc. Therefore, most of the retrieved papers have been published in IT-oriented and not in managerial journals.

Table 3: Classification of blockchain-related energy trading literature.

Journals	Number of papers published
IEEE Transactions on Industrial Informatics	6
ELSEVIER International Journal of Electrical Power and Energy Systems	5
IEEE Internet of Things Open Access	3
ELSEVIER Renewable and Sustainable Energy Reviews	3
ELSEVIER Applied Energy	3
IEEE Transactions on Intelligent Transportation Systems	2
IEEE International Journal of Emerging Electric Power Systems	2
IEEE Transactions on Industry Applications	2
IEEE Transactions on Smart Grid	1
IEEE Transactions on Green Communications & Networking	1
IEEE Communications Magazine	1
IEEE Transactions on Systems, Man, and Cybernetics	1
IEEE Transactions on Services Computing	1
ELSEVIER Journal of Information Security and Applications	1
ELSEVIER Energy Reports Open Access	1
ELSEVIER Journal of Network and Computer Applications	1
ELSEVIER Computers in Industry	1
ELSEVIER Computer Communications	1
MDPI Electronics (Switzerland), Open Access	1
MDPI Applied Sciences (Switzerland)	1
ACM Transactions on Internet Technology	1
Hindawi, Mobile Information Systems, Open Access	1

3. Retrieved Literature Taxonomy

3.1. TAXONOMY

The classification and analysis of the selected literature (40 papers) is depicted below. As already mentioned, two (2) thematic areas of research interest have been identified in blockchain-enabled energy trading implementations (see Figure 10). Based on them, key technical characteristics are being derived and the implementation maturity of the available blockchain-related energy trading mechanisms are being evaluated.

3.1.1. Blockchain based energy trading implementations in the Smart Grid

In [1], the authors address the problems of energy (carbon) trading, energy dispatch and third-party institutions in the traditional integrated energy market, and based on the advantages of blockchain smart contract, such as high efficiency, security and automatic execution design the cloud service platform (CSP) for an integrated energy market. The energy suppliers and energy users use the Digital Currency Electronic Payment (DCEP) to trade energy (carbon) in the blockchain smart contract provided by the cloud service platform, as well as implement decentralized intelligent dispatch by using blockchain Internet of things technology (See Figure 11).

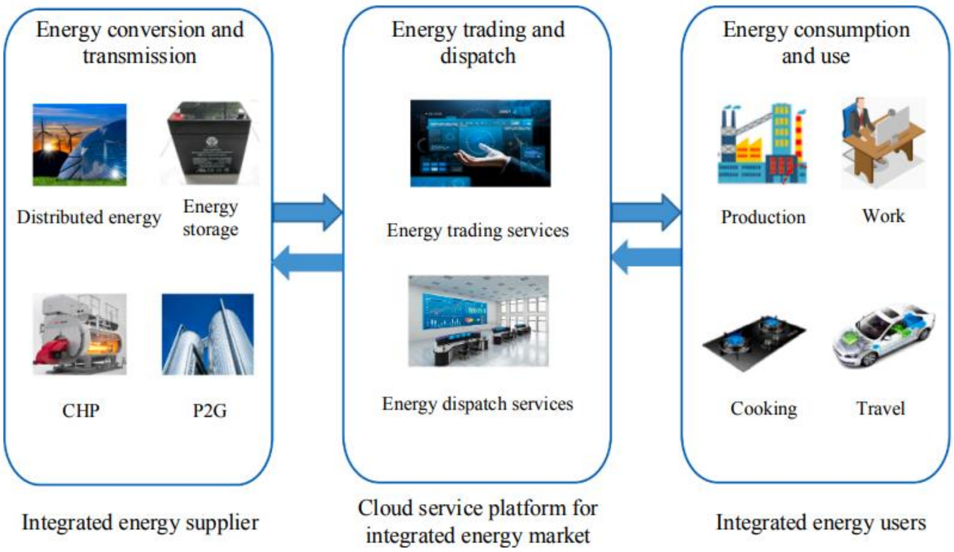


Figure 11. Cloud service platform structure of the integrated energy market. Reprinted from "Design of integrated energy market cloud service platform based on blockchain smart contract" by Lei Wang, Yichao Ma, Liuzhu Zhu, Xuli Wang, Hao Cong, Tiancheng Shi, International Journal of Electrical Power and Energy Systems, Volume 135, Article number 107515, February 2022, page 2. Copyright (2022) by title of publisher.

In order to realize the function of the cloud service platform, this paper uses the online contract development tool-Cloud IDE provided by Blockchain-as-a-Service (BaaS) platform to develop a smart contract. Then, the CSP smart contract is released to Antchain (a new generation of blockchain technology) and checked for its effectiveness. At present, consensus algorithms implemented in Antchain system include PBFT and HoneyBadgerBFT. Antchain adopts large-scale node consensus to realize storage consensus and fast confirmation. It supports multi class programming languages, while, based on the node key management of the trusted execution environment, it achieves the encryption of the whole data transmission process. The comparison between Antchain and typical blockchain technology is shown in Figure 12.

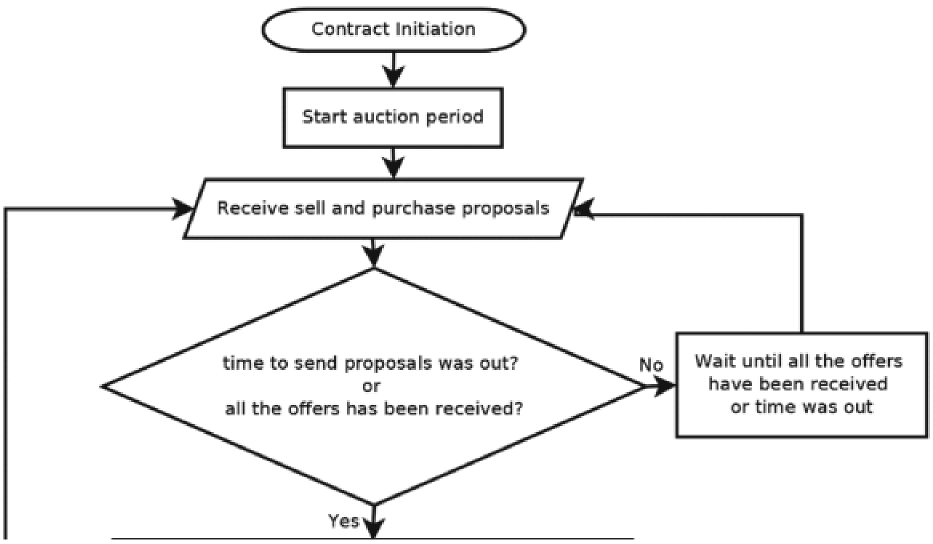
Table 1
Comparison of typical blockchain Technology.

Blockchain Technology	Encryption algorithm	Consensus mechanism	Smart contract	Speed	Cost
Bitcoin	SHA-256	PoW	No	Slow	Expensive
Ethereum	Ethash	PoS	Yes	Medium	Medium
Antchain	ECC/SMX	PBFT , etc	Yes	Fast	Cheap

Figure 12. Comparison of typical blockchain Technology. Reprinted from "Design of integrated energy market cloud service platform based on blockchain smart contract" by Lei Wang, Yichao Ma, Liuzhu Zhu, Xuli Wang, Hao Cong, Tiancheng Shi, International Journal of Electrical Power and Energy Systems, Volume 135, Article number 107515, February 2022, page 3. Copyright (2022) by title of publisher.

In [2], the authors propose a permissioned blockchain-based framework for energy management. This P2P approach, combined with demand and production forecasting, proposes a new paradigm, where both sellers and buyers are able to exchange energy.

The energy purchases and sales are guided by a predictive algorithm that always informs the user about the excess of energy that will be available to be sold, as well as the energy requirements according to the demand for the energy purchases (See Figure 13).



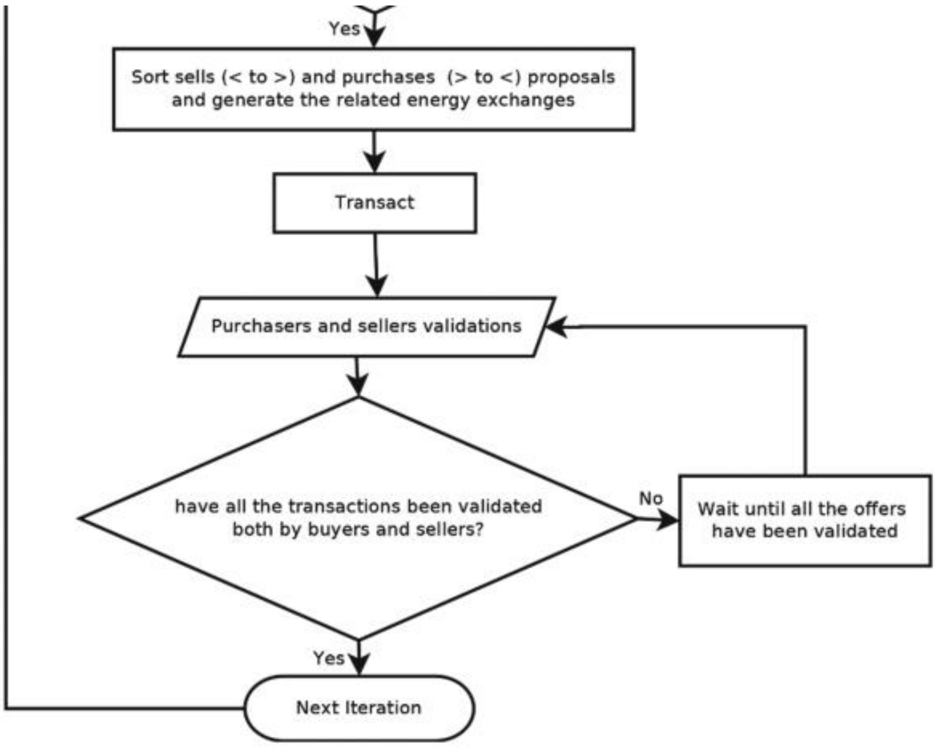


Figure 13. Flow chart of the automatic auction mechanism. Reprinted from "Energy Trading Between Prosumers Based on Blockchain Technology" by Susana M. Gutiérrez, José L. Hernández, Alberto Navarro and Rocío Viruega, Notes in Networks and Systems, Volume 320 LNNS, 2022, page 30. Copyright (2022) by title of publisher.

The smart contract is the core of the solution. It allows the users to interact and exchange energy between prosumers promoting renewable energy communities for energy transition. The authors run simulation tests on case studies in order to evaluate the performance of the proposed framework (See Figure 14).

Figure 14. Sample of the transaction for the purchase confirmation. Reprinted from "Energy Trading Between Prosumers Based on Blockchain Technology" by Susana M. Gutiérrez, José L. Hernández, Alberto Navarro and Rocío Viruega, Notes in Networks and Systems, Volume 320 LNNS, 2022, page 31. Copyright (2022) by title of publisher.

In [54], a differentially private Energy Auction for blockchain-based microgrid systems (DEAL) is developed. The differential privacy technique is being used, in order to make the auction more private and secure. The Consortium blockchain minimizes the complexity at every trading node. The authors compare the DEAL with the Vickrey–Clarke–Groves (VCG) auction scenario and the experimental results demonstrate that DEAL outperforms VCG mechanism by maximizing sellers' revenue along with maintaining overall network benefit and social welfare (See Figure 15).

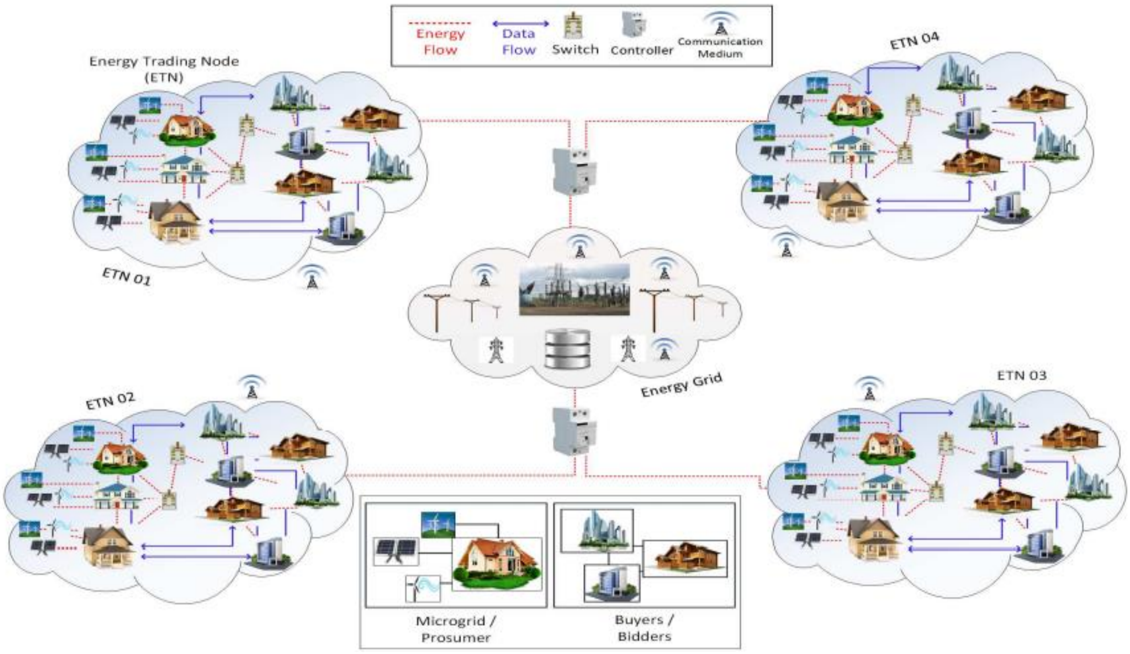


Figure 15. System model of the DEAL strategy describing the complete auction scenario between microgrid buyers and energy power. Reprinted from "DEAL: Differentially Private Auction for Blockchain based Microgrids Energy Trading", by Muneeb Ul Hassan, Mubashir Husain Rehmani, Jinjun Chen, Transactions on Services Computing 13(2),8869938, 2021, page 4. Copyright (2021) by title of publisher.

In [53], the authors present FeneChain, a blockchain based energy trading scheme to supervise and manage the energy trading process for Industry 4.0. A consortium blockchain among energy brokers is built in order to verify and record energy trading transactions. Security and privacy analysis as well as performance evaluation (i.e., computational costs and communication overhead) are being provided by implementing a prototype via a local Ethereum test network and Raspberry Pi. FeneChain achieves efficient management, transparency, unforgeability, and verifiability of energy trading data and guarantees energy trading fairness against malicious energy sellers. Additionally, FeneChain exhibits its power especially when some energy purchaser cannot connect to the utility company, but it can communicate with nearby energy sellers. This improves energy utilization for residential users greatly, while for the utility company, which mainly monitors energy consumption and distributes energy upon multiple energy requests, the FeneChain further assists in handling energy exchanges with many energy sellers and energy purchasers offering trustworthy trading (See Figure 16).

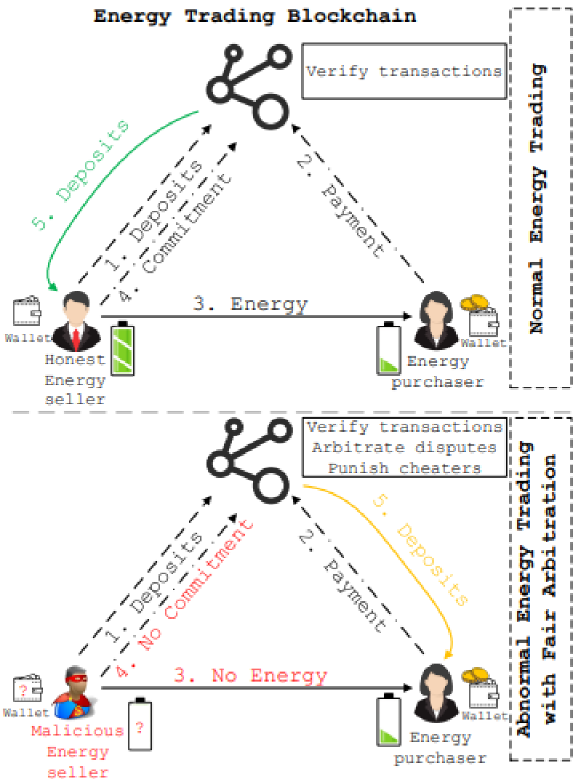


Figure 16. The illustration of energy trading from two aspects. Reprinted from "Blockchain-enabled Secure Energy Trading with Verifiable Fairness in Industrial Internet of Things", by Meng Li, Donghui Hu, Chhagan Lal, Mauro Conti, Zijian Zhan. Transactions on Industrial Informatics 16(10),9000864, 2020. Copyright (2020) by title of publisher.

In [26], the authors are concerned with the development of a new decentralized P2P energy trading platform, called DeTrade, which consists of two key layers: the market layer (DeMarket) and the blockchain (See Figure 17). The market layer consists of a short-term multi-staged multi-period market with a uniform pricing mechanism and features a parallel and short-term pool-structured auction. It is cleared using a novel decentralized Ant-Colony Optimization (DACO) method, that provides a near-optimal market solution (in terms of the maximum social welfare) within a limited number of stages. The DeMarket is coupled with a highly secured and automated blockchain layer that ensures fast and real-time settlements. A smart contract is being implemented in the Solidity programming language and deployed on a permissioned blockchain using Hyperledger Burrow. The smart contract manages the digital Eurotokens balance, stores and verifies the market clearing results, and ensures that the digital tokens are correctly re-distributed from buyers to sellers, thus generating trust among prosumers and eliminating any potential privacy violations (See Figure 18).

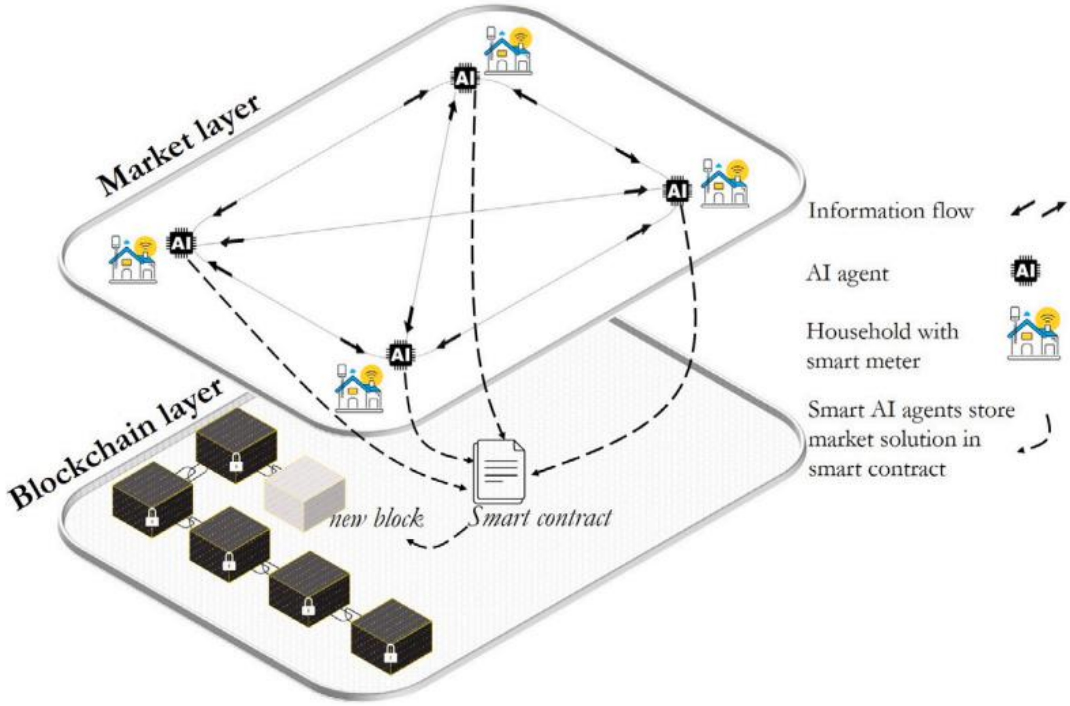


Figure 17. The decentralized local energy trading platform architecture (DeTrade). Reprinted from "A novel decentralized platform for peer-to-peer energy trading market with blockchain technology" by Ayman Esmat, Martijn de Vos, Yashar Ghiassi-Farrokhfal, Peter Palensky, Dick Epema, Applied Energy Volume 282, Part A, 116123, Jan. 2021. Copyright (2021) by title of publisher.

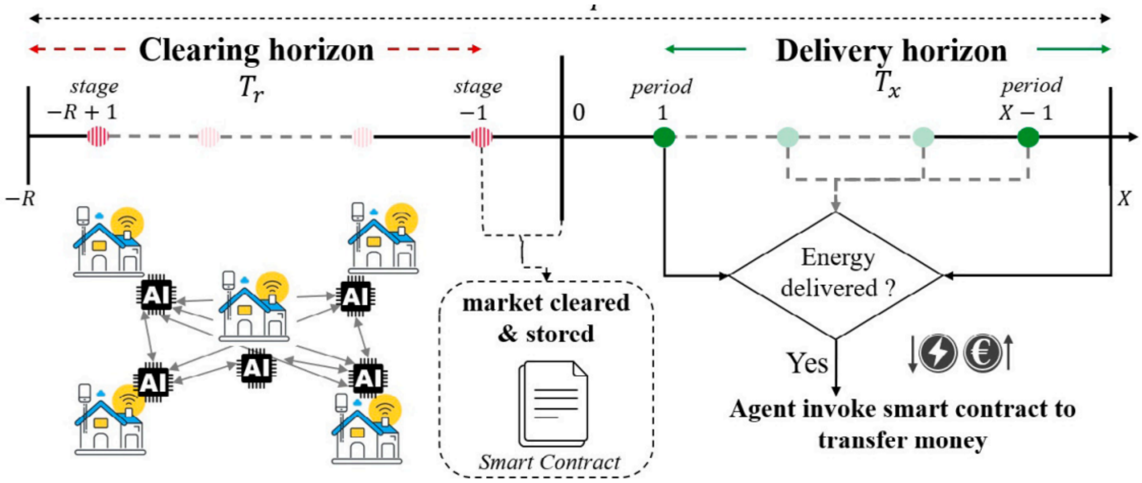
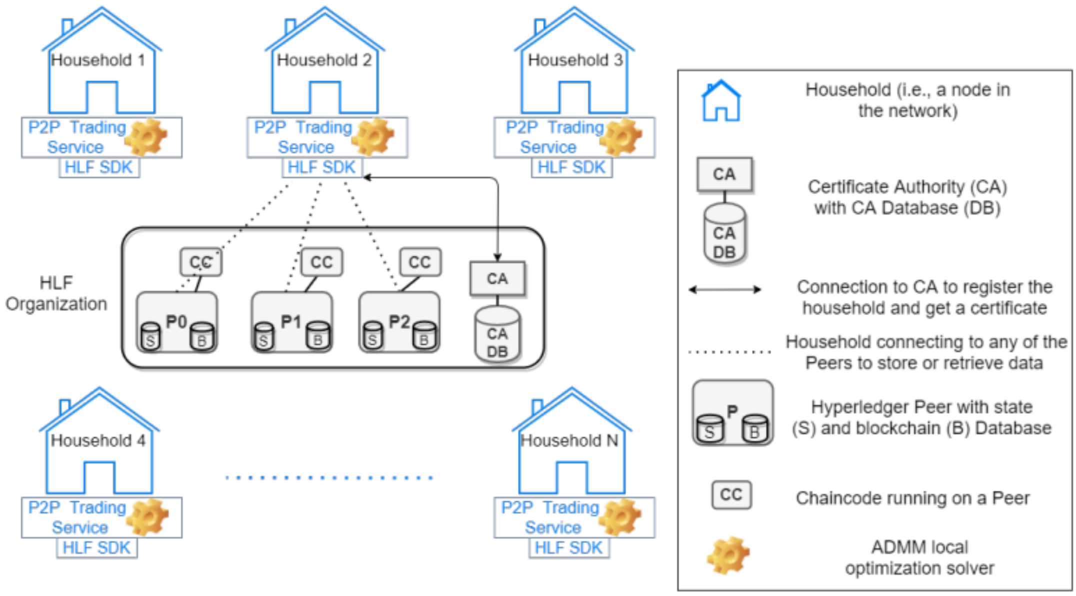
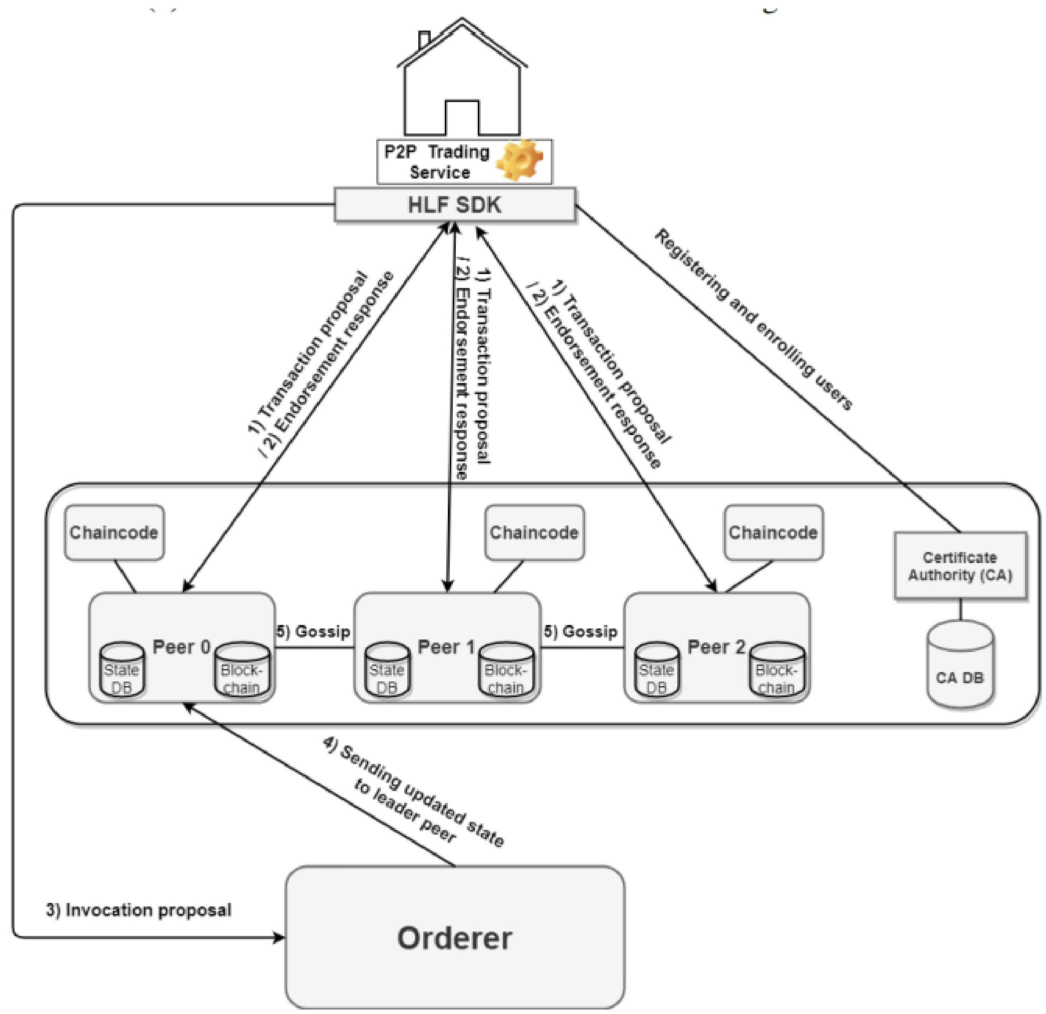


Figure 18. DeMarket structure: Market 'Clearing' horizon (Tr) with R trading 'stages' and 'Delivery' horizon (Tx) with X delivery 'periods'. Reprinted from "A novel decentralized platform for peer-to-peer energy trading market with blockchain technology" by Ayman Esmat, Martijn de Vos, Yashar Ghiassi-Farrokhfal, Peter Palensky, Dick Epema, Applied Energy Volume 282, Part A, 116123, Jan. 2021. Copyright (2021) by title of publisher.

In [4], two strategies regarding the bilateral trading preferences of households participating in a fully Peer-to-Peer (P2P) local energy market are presented. The first strategy is based on the matching between the surplus power supply and the demand of the participants, while the second is based on the distance between them in the network. The impact of the bilateral trading preferences on the price and amount of energy traded is assessed for the two strategies (See Figure 19). A decentralized fully P2P energy trading market is developed to generate the results in a day-ahead setting. A permissioned blockchain-smart contract platform is used for the implementation of the decentralized P2P trading market on a digital platform. Real data from a residential neighbourhood, with different varieties of distributed energy resources, located in the city of Amsterdam is used for the simulations. Results show that in the two strategies, the energy procurement cost and the grid interaction of all participants in P2P trading are reduced compared to a baseline scenario. The total amount of P2P energy traded is found to be higher when the trading preferences are based on distance, which could also be considered as a proxy to enhance energy efficiency in the network by encouraging P2P trading among nearby households. The simulation results show that the P2P trading of locally produced renewable energy can help in reducing the interaction with the main grid, resulting in a more efficient and sustainable use of energy.



(a) Households communication with the HLF organization.



(b) Consensus protocol for each household within the considered HLF organization.

Figure 19. The HLF-based P2P energy trading network architecture. Reprinted from "Blockchain-Based Fully Peer-to-Peer Energy Trading Strategies for Residential Energy Systems", by Tarek AlSkaif, Jose L. Crespo-Vazquez, Milos Sekuloski, Gijs van Leeuwen and João P. S. Catalão, Transactions on Industrial Informatics, Volume 18, Issue 1, 2022. Copyright (2022) by title of publisher.

In [11], the authors present a Proof-of-Stake (PoS) public blockchain-based pricing scheme for the P2P energy trading market, where miners are rewarded with successful mining or punished by losing their stake adversely. The payment system is supported by the proposed blockchain system with the utilization of a crypto-currency type named elecoin (See Figure 20). The transactions are verified by all prosumers with the microgrid. The miners are selected based on their invested stake. The miners sacrifice part of their stake to compensate for the power losses and reduce the price gap from the traditional prosumer-to-grid trading (Feed-in-tariff).

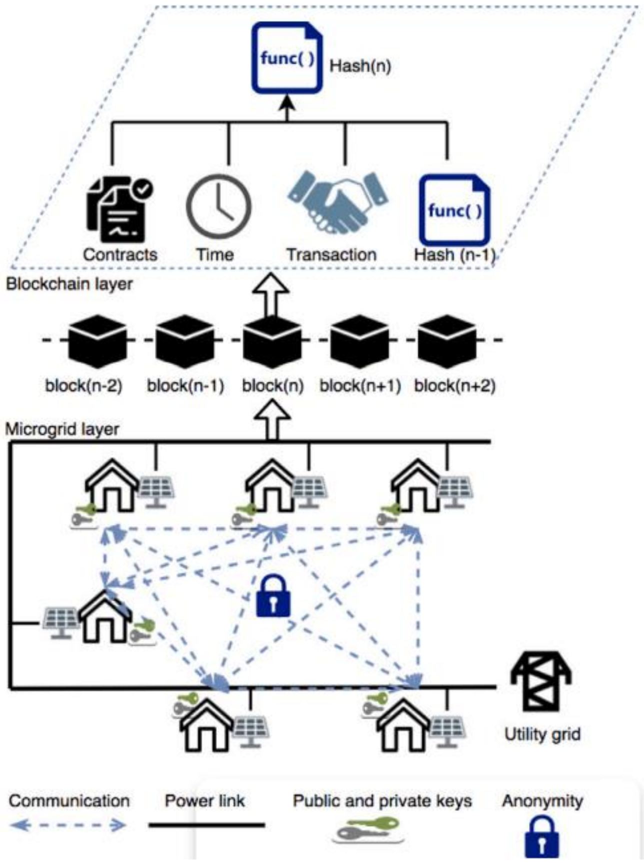


Figure 20. The structure of the P2P energy trading supported by blockchain system. Reprinted from "A Proof-of-Stake public blockchain based pricing scheme for peer-to-peer energy trading" by Jiawei Yang, Amrit Paudel, Hoay Beng Gooi, Hung Dinh Nguyen, Applied Energy, Volume 29815, Article number 117154, September 2021. Copyright (2021) by title of publisher.

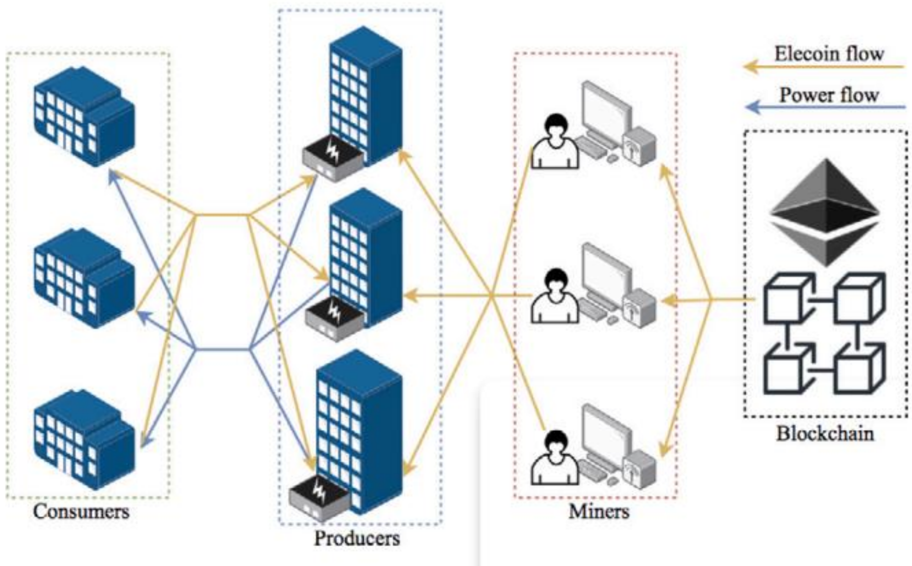


Figure 21. The role of miners in P2P energy trading. Reprinted from "A Proof-of-Stake public blockchain based pricing scheme for peer-to-peer energy trading" by Jiawei Yang, Amrit Paudel, Hoay Beng Gooi, Hung Dinh Nguyen, Applied Energy, Volume 29815, Article number 117154, September 2021. Copyright (2021) by title of publisher.

The proposed model contributes to increase the social welfare by improving the producers' income and the consumers' cost-saving through the designed pricing scheme, which eliminates the price gap between buying and selling. Successful mining is encouraged by rewards accordingly. A case study is introduced where a microgrid model with 27 prosumers is tested with the PoS public blockchain-based pricing scheme (See Figure 21). The process of model implementation and smart contract creation are demonstrated. Numerical results prove the feasibility and effectiveness of the proposed method.

In [13], a blockchain-assisted adaptive model, namely SynergyChain, is presented for improving the scalability and decentralization of the prosumer grouping mechanism in the context of peer-to-peer energy trading (See Figure 22). Smart contracts are used to store the transaction information and to create the prosumer groups. SynergyChain integrates a reinforcement learning module to further improve the overall system performance and profitability. It is developed using Python and Solidity and it has been tested using Ethereum test nets. The comprehensive analysis using on the hourly energy consumption dataset shows a 39.7% improvement in the performance and scalability of the system as compared to the centralized systems.

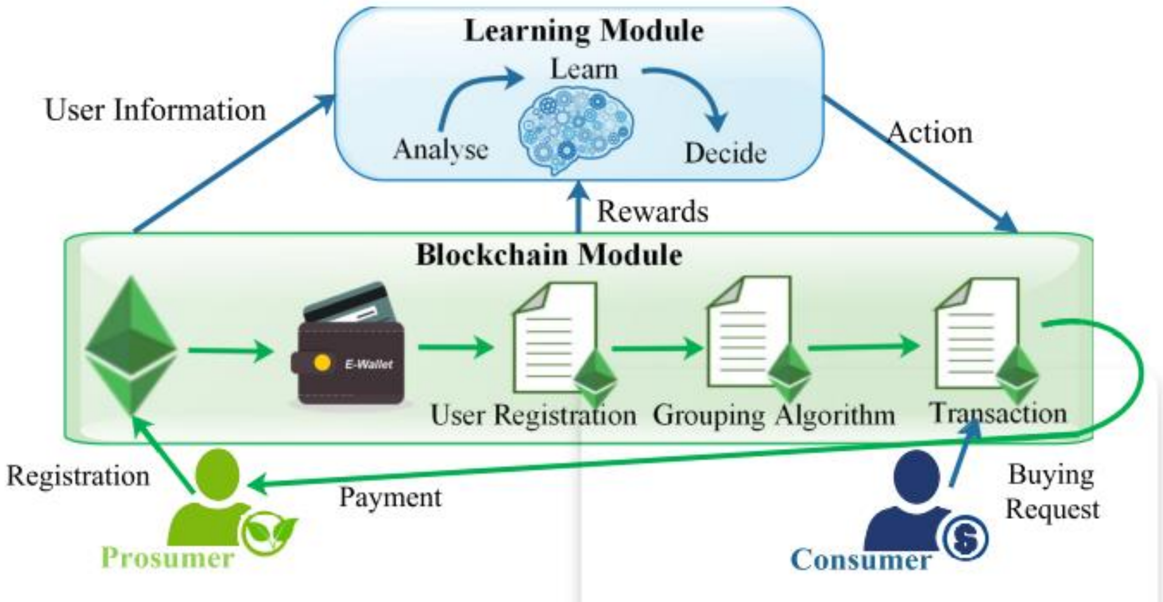


Figure 22. Architecture overview of SynergyChain. Reprinted from "SynergyChain: Blockchain-Assisted Adaptive Cyber-Physical P2P Energy Trading", by Faizan Safdar Ali, Ouns Bouachir, Öznur Özkasap and Moayad Aloqaily, Transactions on Industrial Informatics, Volume 18, Issue 7, Aug. 2021. Copyright (2021) by title of publisher.

In [17], the authors propose a Unified permissioned blockchain-based P2P-ET Architecture (UBETA) that integrates three different types of energy markets and provides a unified energy trading and payment settlement model. The UBETA system is based on an enterprise Ethereum Blockchain, known as Hyperledger Besu, and on the Istanbul Byzantine Fault Tolerance (IBFT) consensus algorithm. Comparisons made between the performance of the proposed IBFT-based system with three existing systems (i.e., Ethereum Clique, Ethereum Proof of Work and Hyperledger Fabric's Raft) in terms of transaction latency, transaction throughput and fail rate prove the outperformance of the proposed system (See Figure 23).

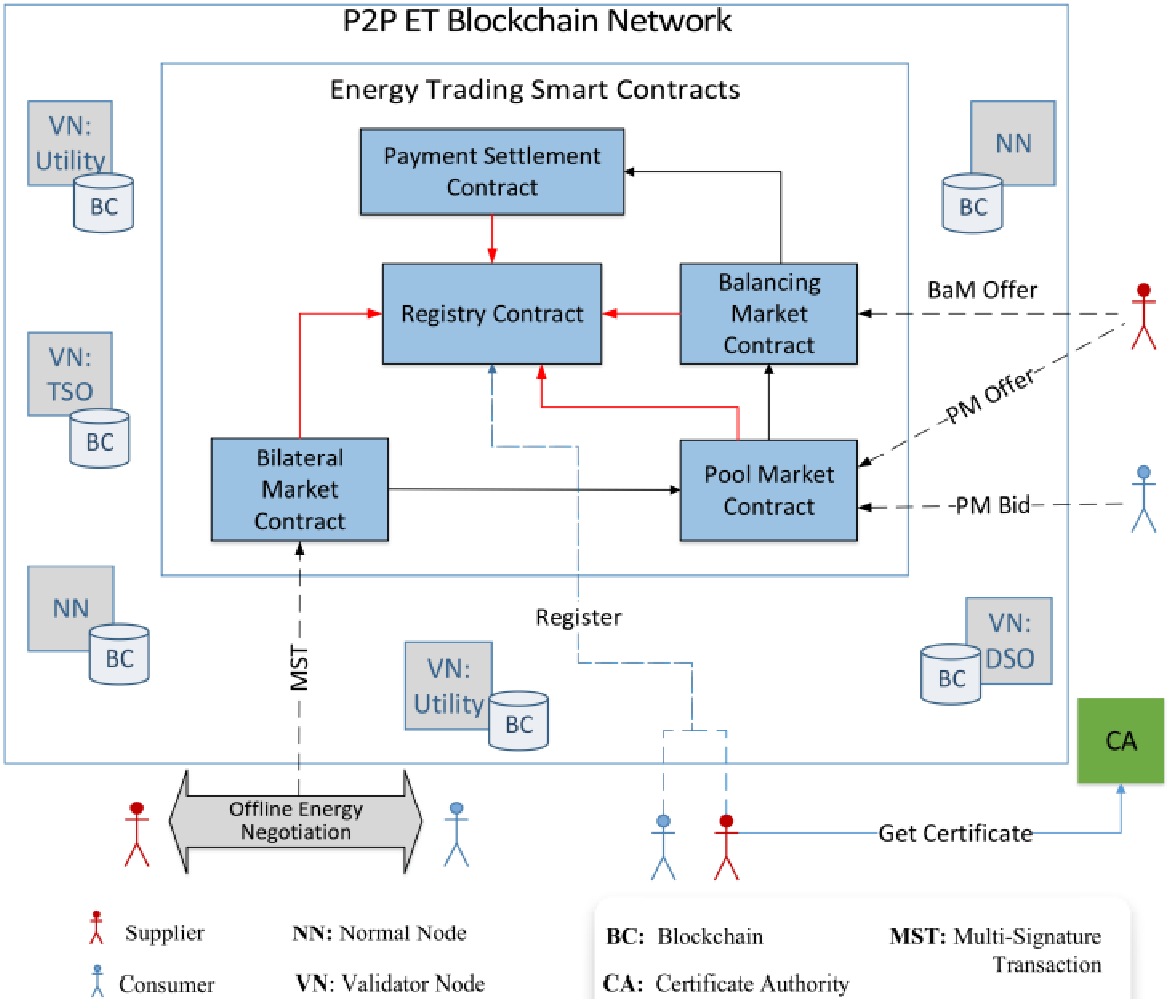


Figure 23. Blockchain Based P2P-ET Architecture. Reprinted from "An Architecture and Performance Evaluation of Blockchain-Based Peer-to-Peer Energy Trading" by Juhar Abdella, Zahir Tari, Adnan Anwar, Abdun Mahmood, Fengling Han, Transactions on Smart Grid, Volume 12, Issue 4, Article number 9344670, July 2021. Copyright (2021) by title of publisher.

In [20], a trustworthy and incentivized framework for smart grid energy trading using distributed ledger technology and smart contracts is proposed (See Figure 24). Smart contracts are utilized for energy injection into smart grid, energy bidding to submit energy demand, energy trading and energy utilization. These contracts run on an ethereum blockchain platform with the proof of stake (PoS) consensus mechanism. An iterative Vickrey–Clarke–Grove (Vickrey auction) method for the incentivized energy trading in context of both prosumers and consumers is being applied.

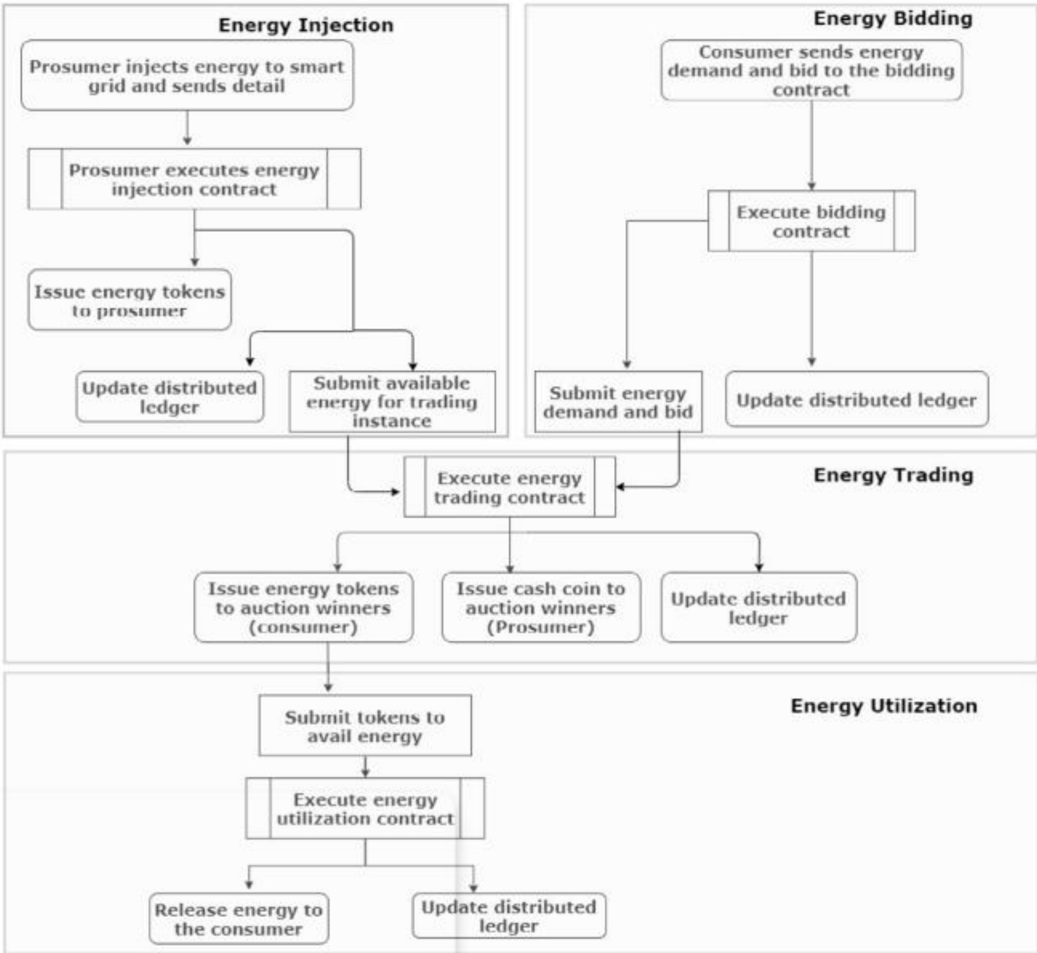


Figure 24. Workflow of the proposed framework in [20]. Reprinted from "A trustworthy and incentivized smart grid energy trading framework using distributed ledger and smart contracts", by Ajit Muzumdar, Chirag Modi, Madhu G.M., C. Vyjayanthi, Journal of Network and Computer Applications, Volume 183-1841, Article number 103074, June 2021. Copyright (2021) by title of publisher.

In [24], an energy trading scheme, called HO-TRAD, is proposed to improve the efficiency of model trading while ensuring the fairness of energy trading by introducing an entity's active reputation value (See Figure 25). Based on the identity verification foundation of the consortium chain, the scheme enhances the existing PBFT consensus algorithm and improves the efficiency of the model transactions (more consistent with the IoT energy trading scenario from the perspective of transaction fairness).

In [25], the authors work towards the trust issues among the energy exchanging networks, by presenting a Blockchain based Confidential Consortium (CoCo) P2P energy trading system that creates a trusted network on nodes, where participants identities are known and controlled. A Java-script-based smart contract is sent over the Microsoft CoCo system using the Proof of Elapsed Time (PoET) consensus protocol.

In [38], an automated demand response (ADR) framework for decentralized scheduling and secure peer-to-peer (P2P) trading among energy storage systems in energy local networks (ELNs) is presented. Different from most existing works that trade electricity over long distances and through complex meshes, this proposed work performs decentralized and automated demand response through energy sharing of P2P executors (See Figure 25).

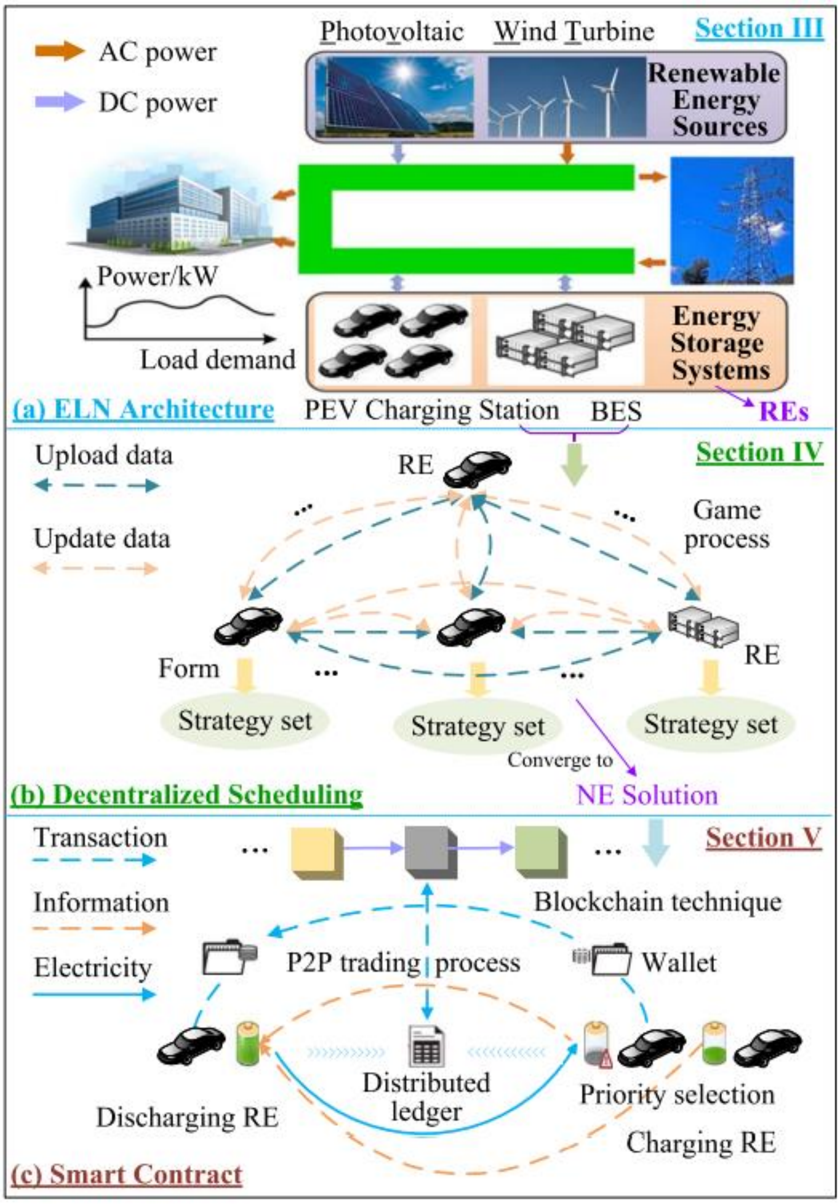


Figure 25. (a) Architecture of the ELN system. (b) and (c) Illustration of the proposed automated demand response (ADR) method. Reprinted from "Automated Demand Response Framework in ELNs: Decentralized Scheduling and Smart Contract" by Xiaodong Yang, Guofeng Wang, Haibo He, Junjie Lu, and Youbing Zhang. Transactions on Systems, Man, and Cybernetics: Systems, Volume: 50, Issue: 1, Jan. 2020. Copyright (2020) by title of publisher.

To achieve decentralized scheduling without relying on a central entity, a price-incentive noncooperative game theoretic model is introduced to produce equilibrium solutions for energy storage systems, while an evaluation system to match trading pairs involving buying and selling nodes is being developed. On this basis, a state-machine driven smart contract mechanism is built to realize P2P trading without reliance on a trusted third party.

In [39], an integrated blockchain-based energy management platform is proposed that optimizes energy flows in a microgrid whilst implementing a bilateral trading mechanism (See Figure 26). (1) In the physical layer, power flows in the horizontal dimension between households through grid connections. (2) Information is exchanged in the vertical dimension between the economic and the physical layer. (3) In the economic layer, a trading mechanism is used to enable monetary compensation for power injections and withdrawals into/from the grid. (4) Information is exchanged between the information layer and the layers below. (5) The households send their locally calculated optimal schemes for the economic and physical layers to the smart contract. Physical constraints in the microgrid are respected by formulating an Optimal Power Flow (OPF) problem, which is combined with a bilateral trading mechanism in a single optimization problem. The Alternating Direction Method of Multipliers (ADMM) is used to decompose the problem to enable distributed optimization and a smart contract is used as a virtual aggregator. This eliminates the need for a third-party coordinating entity. The smart contract fulfills several functions, including distribution of data to all participants and executing part of the ADMM algorithm. The model is run using actual data from a prosumer community in Amsterdam. Several scenarios of the model are tested to evaluate the impact of combining physical constraints and trading on the social welfare of the community and on the scheduling of energy flows. Simulation results show that the import costs of the whole community are reduced.

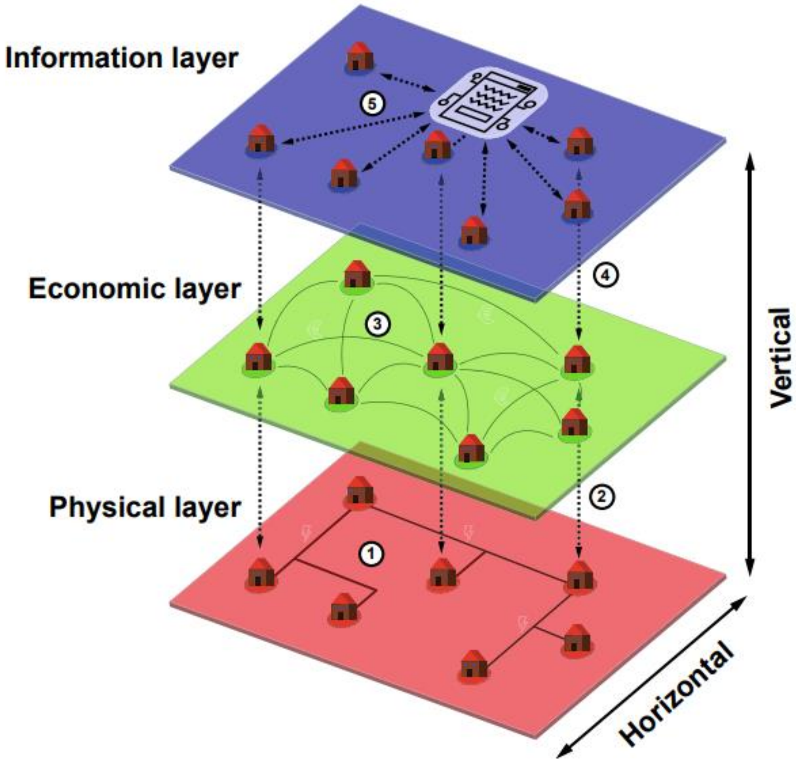


Figure 26. Illustration of the different layers of the proposed model and the interaction between them. Reprinted from "An integrated blockchain-based energy management platform with bilateral trading for microgrid communities" by Gijs van Leeuwen, Tarek AlSkaif, Madeleine Gibescu, Wilfried van Sark, Applied Energy 263 (2020) 114613, Feb. 2020. Copyright (2020) by title of publisher.

In [45], a blockchain-based decentralized secure energy trading system (SETS) framework is proposed for storing and processing the data generated from smart meters (SMs) (See Figure 27). In SETS, miner node is designated to validate the requests of energy requirements, dynamic pricing, and time of stay. The consumers can generate and sell energy by keeping Energy Trading (ET) transactions in the blockchain network. In SETS, ETCoin is used as a cryptocurrency for ET transactions in the private blockchain network. The evaluation results obtained show that SETS outperforms TETS (traditional energy trading system), in terms of computation time and communication costs.

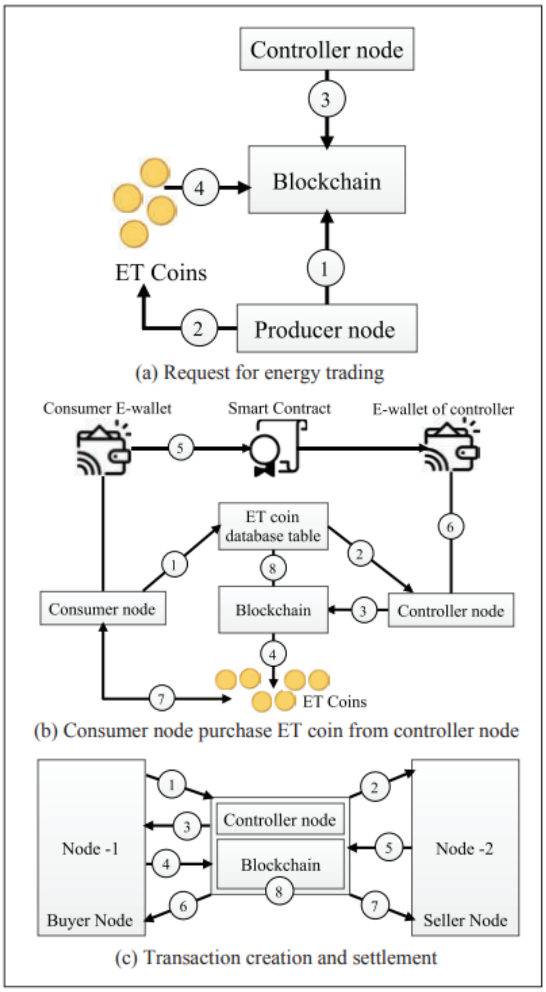


Figure 27. The workflow of the secure energy trading system. Reprinted from "When Blockchain Meets Smart Grid: Secure Energy Trading in Demand Response Management", by Aparna Kumari, Rajesh Gupta, Sudeep Tanwar, Sudhanshu Tyagi, and Neeraj Kumar,. IEEE Network, Aug. 2020. Copyright (2020) by title of publisher.

Another approach towards achieving regional energy balance and reduction of carbon emissions on distribution networks is proposed in [46] through a novel P2P trading framework to exchange energy and carbon allowance (See Figures 28 & 29). The trading is proceeded under the standardised and self-enforcing smart contract. The optimal bidding/selling prices of prosumers and the energy reshaping decisions are yielded by the proposed prosumer-centric and microgrid-trader-centric algorithms in order to achieve a regional energy balance. Prosumer A supplies surplus energy to prosumer B. Prosumer A needs to have the carbon allowance (r_{allow},t) when supplying energy to prosumer B. The designed decentralised low carbon incentive mechanism provides macro policy makers with a potential policy design for carbon mitigation in the energy sector, which allows the monetary incentive of carbon reduction to be accurately allocated according to the real-time prosumption behaviours in a specific location and a certain time period.

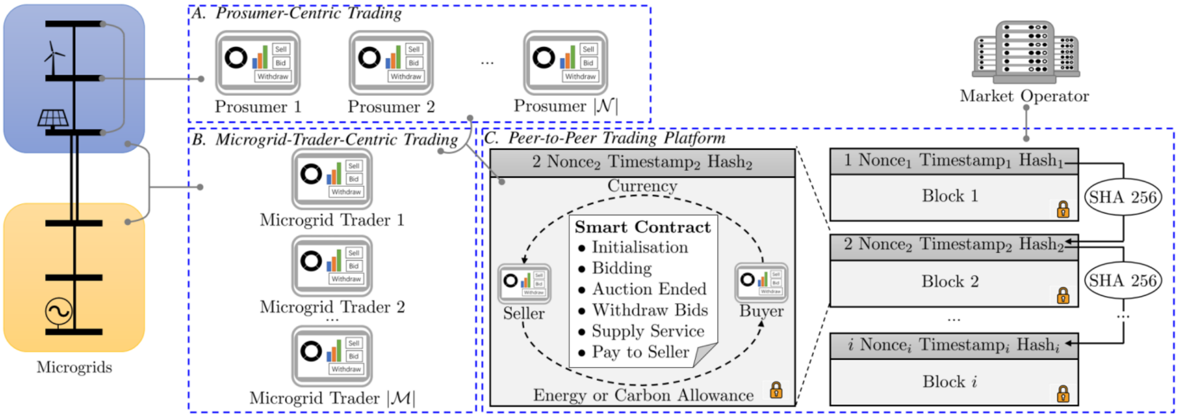


Figure 28. A novel P2P trading framework to exchange energy and carbon allowance a) Individual prosumers trade energy or carbon allowance on the layer of prosumer-centric trading. b) The residual supply and demand for an ensemble of prosumers in the same microgrid are aggregated and traded by microgrid-traders on the layer of microgrid trader-centric trading. c) The trading of energy or carbon allowance is proceeded on the layer of peer-to-peer trading platform. Reprinted from "A blockchain based peer-to-peer trading framework integrating energy and carbon markets", by Weiqi Hua, Jing Jiang, Hongjian Sun, Jianzhong Wu, Applied Energy 279(7774):115539, Dec. 2019, Copyright (2020) by title of publisher.

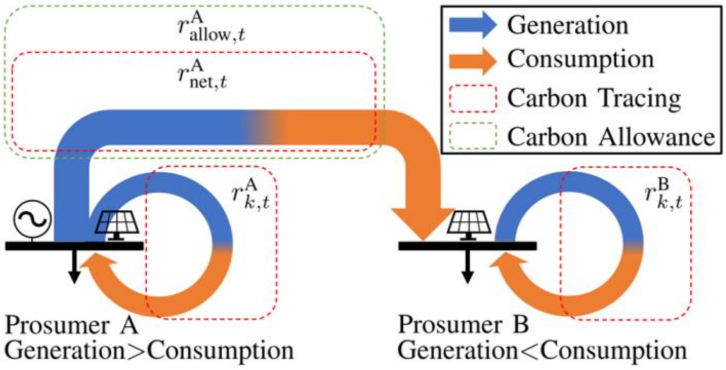


Figure 29. Schematic illustration of carbon emissions tracing in a microgrid. Reprinted from "A blockchain based peer-to-peer trading framework integrating energy and carbon markets".

Another novel idea is presented by the authors in [47], which uses a secure private blockchain (SPB) framework in which, energy producers and consumers directly negotiate the energy price (See Figure 30). A routing method which routes packets based on the destination public key (PK) is used to reduce the associated overheads. SPB eliminates the reliance on trusted third party TTP to ensure that both the energy producer and the consumer commit to their obligations by introducing atomic meta-transactions. The latter consists of two transactions: first the consumer generates a commit-to-pay (CTP) transaction, committing to pay the energy price to the producer. On receipt of the energy, the smart meter of the consumer generates an energy receipt confirmation (ERC) which triggers a smart contract to transfer the committed price in CTP to the energy producer.

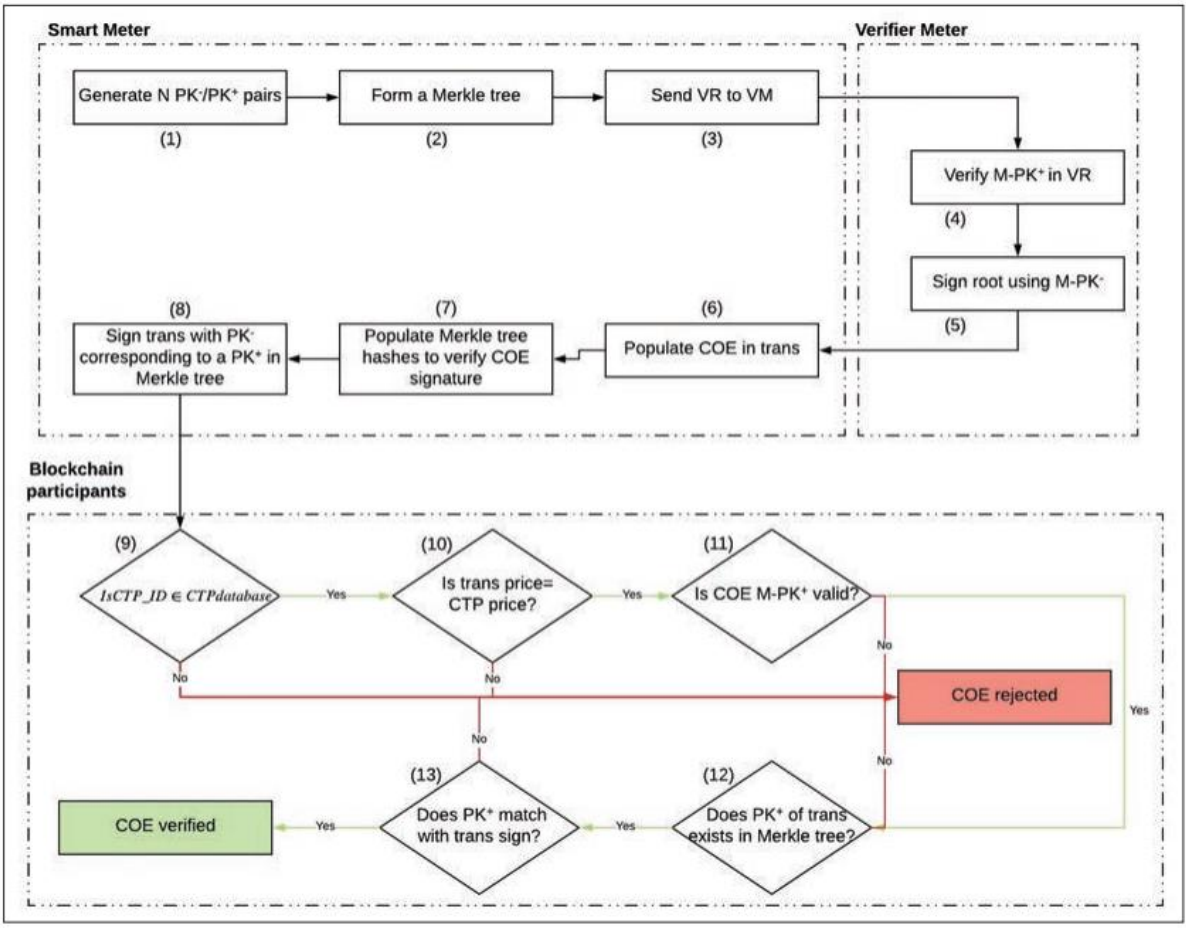


Figure 30. Certificate of Existence (CoE) and usage process. Reprinted from "SPB: A Secure Private Blockchain-Based Solution for Distributed Energy Trading", by Ali Dorri, Fengji Luo, Salil S. Kanhere, Raja Jurdak, IEEE Communications Magazine 57(7):120-126, Jul. 2019. Copyright (2019) by title of publisher.

To verify that the ERC is generated by a genuine smart meter, SPB supports the authentication of anonymous smart meters to prevent malicious nodes from linking the ERC transactions and thus, to enhance the user privacy. Qualitative security analysis shows the resilience of SPB against a range of attacks, whilst the implementation results demonstrate that SPB reduces monetary costs and delays compared to existing solutions.

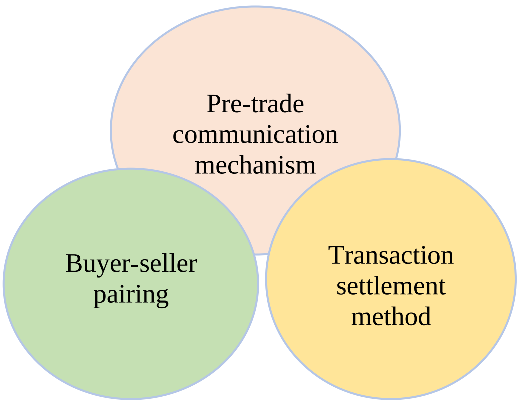


Figure 31. Energy Transactions of Blockchain-based Energy Trading

Table 4. Comparison of the different features extracted from the literature regarding Energy Trading implementations in Smart Grids.

Source	Methodology	Product (s)	Sustainability Perspective
[1]	Architectural development, testing, performance analysis	A cloud service platform of integrated energy market.	Social, Economic, Environment al
[2]	Architectural Analysis, Case Study tests	A paradigm based on blockchain in the energy trading market, where both sellers and buyers are able to exchange energy.	Social, Economic, Environment al
[54]	System design, testing, performance analysis	A differentially private Energy Auction for blockchain based microgrid systems (DEAL)	Social, Economic
[53]	Architectural development, system design, testing	An energy trading service using a distributed algorithm for the trade mechanism	Social, Economic
[26]	Architectural development, system design, simulation, security tests & performance analysis	A decentralized P2P energy trading platform called DeTrade and a decentralized market clearing method called DACO.	Social, Economic
[4]	Architectural development, system design, comparison tests, case study & simulation, performance analysis	Two bilateral trading coefficients implementations on a blockchain Based P2P energy market	Social, Economic, Economic,
[11]	architectural analysis, process design, case study, performance evaluation	A Proof-of-Stake public blockchain-based pricing scheme using elecoin	Social, Economic
[13]	architectural analysis, process design, testing, performance evaluation	SynergyChain, blockchain assisted adaptive model	Social, Economic
[17]	architectural analysis, performance evaluation	P2P-ET architecture (UBETA) providing a unified energy trading & payment settlement	Economic
[20]	framework presentation, algorithm process design, performance and security analysis	Smart grid energy trading framework, utilizing Ethereum smart contract and employing continuous double auction & uniform-price double-sided auction mechanisms.	Social, Economic
[24]	architecture design, experimental simulation, security analysis	HO-TRAD, a secure energy trading scheme ensuring the fairness of energy trading by introducing an entity's active reputation value.	Social
[25]	architecture design, performance benchmarking	Confidential Consortium (CoCo) P2P energy trading system	Social, Economic

Source	Methodology	Product (s)	Sustainability Perspective
[38]	architectural analysis, process design, performance evaluation, case studies	An automated demand response (ADR) framework for decentralized scheduling & secure peer-to-peer (P2P) trading among energy storage systems in ELNs	Social, Economic
[39]	architectural analysis, model setup, numerical analysis, trading scenarios implementations	A blockchain-based energy management plat-form optimizing energy flows in a microgrid whilst implementing a bilateral trading mechanism.	Social, Economic
[45]	architectural analysis, process design, case study, performance evaluation	SETS, a blockchain-based decentralized frame-work, for storing & processing the data generated from smart meters.	Social, Economic
[46]	architectural development, performance evaluation, comparative analysis	A trading framework enabling the exchange of energy and carbon allowance	Social, Economic
[47]	system design, case studies	A Secure Private BC-based framework enabling energy prosumers to negotiate over the energy price & trade energy	Social, Environment al Economic

3.1.2. Blockchain-based, energy trading implementations in Electrical Vehicles

In [5], the authors present a secure and efficient scheme for Vehicle to Vehicle (V2V) and Vehicle to Grid (V2G) energy trading. In the proposed scheme, energy trading transactions are secured using a consortium blockchain. Local Aggregators (LAGs) are selected as energy brokers, who are responsible for validating the energy trading requests using a Proof of Authority (PoA) consensus mechanism. Moreover, a solution to find the accurate distance with required expenses and time to reach the charging destination is also proposed, which effectively guides EVs to reach the relevant Charging Stations (CSs) and encourages energy trading. A fair payment mechanism is also been proposed, using a smart contract to avoid financial irregularities, whilst an incentive provisioning mechanism ,to prevent EVs from acting selfishly, is also given (See Figure 32).

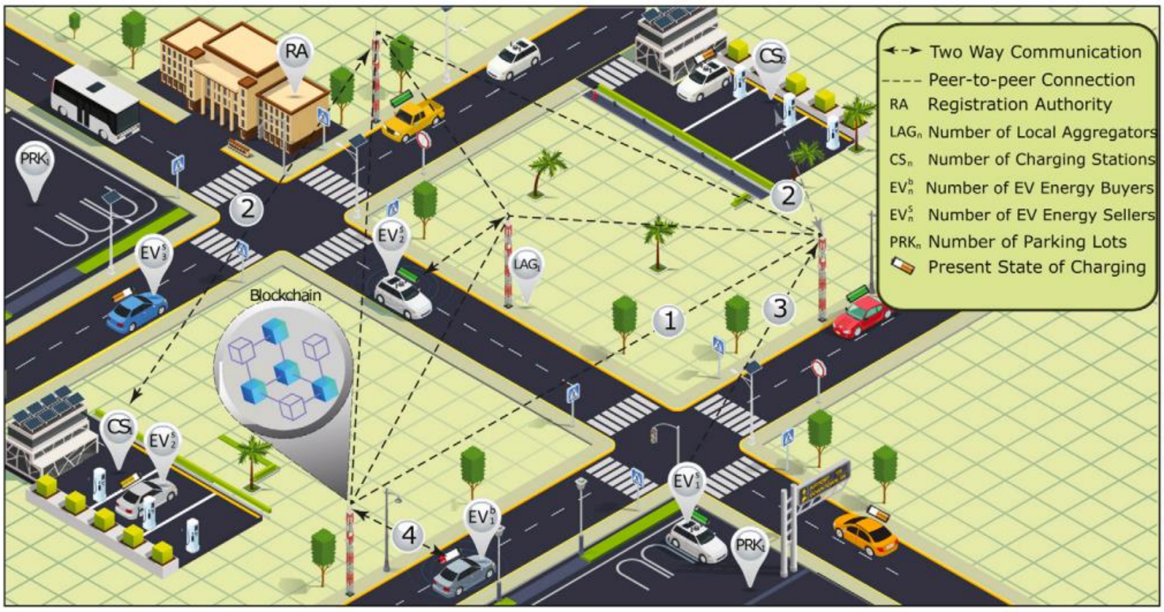


Figure 32. Proposed system model for energy trading. ① LAGs are interconnected in a P2P manner, all energy trading transactions are stored, audited and verified by the authorized LAGs. ② CSs send the energy trading request to the LAGs. They reply back with the notification. ③ Seller EV sends the energy selling request form PRKs to LAGs. ④ Buyer EV gets the information of nearest energy seller with distance and required time and expenses. Reprinted from "A consortium blockchain based energy trading scheme for Electric Vehicles in smart cities", by Rabiya Khalid, Muhammad Waseem Malik, Turki Ali Alghamdi, Nadeem Javaid, Journal of Information Security and Applications, Volume 63, Article number 102998, December 2021. Copyright (2021) by title of publisher.

In [10], the authors propose an advanced Decentralized Electricity Trading Framework (DETF) between Connected Electric Vehicles (CEVs) in parking lots based on a consortium blockchain, Machine Learning, and a Game theoretic model (See Figure 33). A distributed smart contract solution is designed based on a stochastic bidding process which helps CEVs to sell and buy electricity with their maximum profitability. In DETF architecture:

(1) a smart contract is made between all stakeholders and deployed to the blockchain,

(2) New auction is made: a CEV seller which wants to sell electricity stored in its battery, informs the blockchain by its available quantity of electricity for selling,

(3) CEV bidders will submit their bids,

(4) smart contract runs an auction model (based on electricity requested information or game theory) to determine the winner and price,

(5) the selected CEV bidder is awarded the electricity,

(6) the seller is awarded by HLCoin,

(7) the electricity transaction is initiated and

(8) the transaction is finalized.

Numerical simulations with MATLAB Solidity and a comparison of the proposed HLProfitX algorithm to PETCON proves the effectiveness of the proposed solution in terms of revenue.

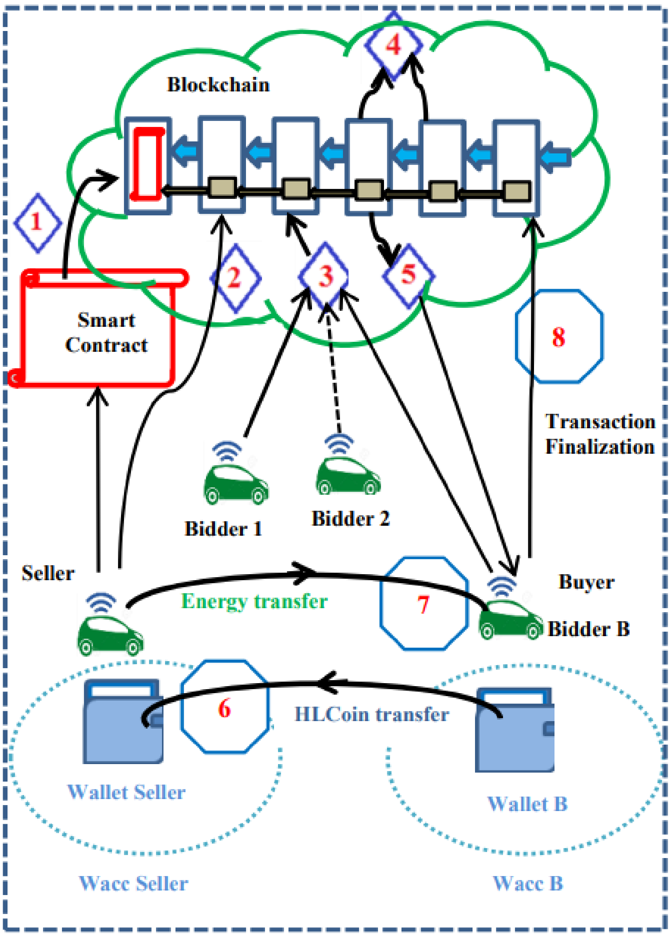


Figure 33. Conceptual Blockchain Architecture for DETF: Reprinted from "A Decentralized Electricity Trading Framework (DETF) for Connected EVs: a Blockchain and Machine Learning for Profit Margin Optimization", by Dhaou Said, IEEE Transactions on Industrial Informatics Volume 17, Issue 10, Article number 9294057, October 2021. Copyright (2021) by title of publisher.

In [14], the authors apply the benefits of Software Defined Networking (SDN) and BlockChain (BC) to the Smart Grid ecosystem to implement a decentralized control mechanism. The proposed scheme employs Ethereum and Smart Contracts to support data security along with an effective DRM (Demand Response Management) during bidirectional energy transfer between EVs and SG (See Figure 34).

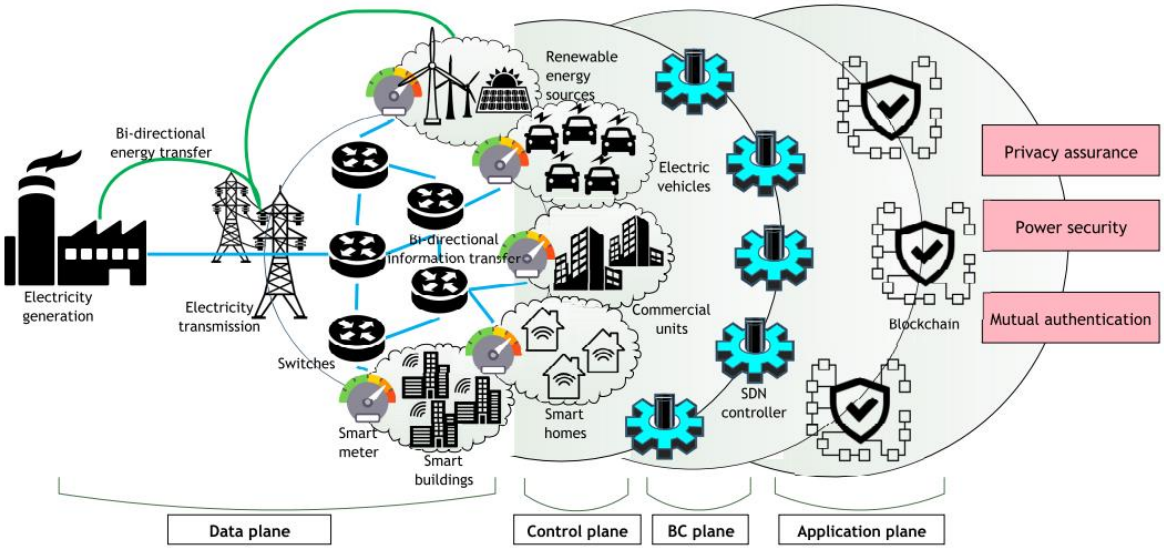


Figure 34. An illustration of the proposed EV-aided SG using Blockchain and SDN. Reprinted from "Blockchain-Based Cyber-Physical Security for Electrical Vehicle Aided Smart Grid Ecosystem", by Kuljeet Kaur, Georges Kaddoum and Sherali Zeadally, IEEE Transactions on Intelligent Transportation Systems Volume 22, Issue 8, August 2021. Copyright (2021) by title of publisher.

In [19], BlockEV, a blockchain-based efficient Charging Station selection protocol, for EVs with the execution of smart contract, is proposed. Two frameworks are being presented. They utilize the smart contract functionality in Ethereum and employ the continuous double auction and uniform-price double-sided auction mechanisms, respectively. The design is further validated by conducting A/B tests to compare the performance of different frameworks on a real world dataset. The results demonstrate that a P2P trading platform that integrates the blockchain technologies with agent-based systems is promising in complementing the current centralized energy grid.

In [37], the authors propose a secure and efficient V2G energy trading framework using consortium blockchain, contract theory, and edge computing. Considering the information asymmetry scenario, they propose an efficient incentive mechanism based on contract theory (See Figure 35). The social welfare optimization problem falls into the category of difference of convex programming and is solved by using the iterative convex–concave procedure algorithm. Edge computing is been incorporated to improve the successful probability of block creation. The computational resource allocation problem is modelled as a two-stage Stackelberg leader–follower game and the optimal strategies are obtained by using the backward induction approach. The performance of the proposed framework is validated via numerical results and theoretical analysis.

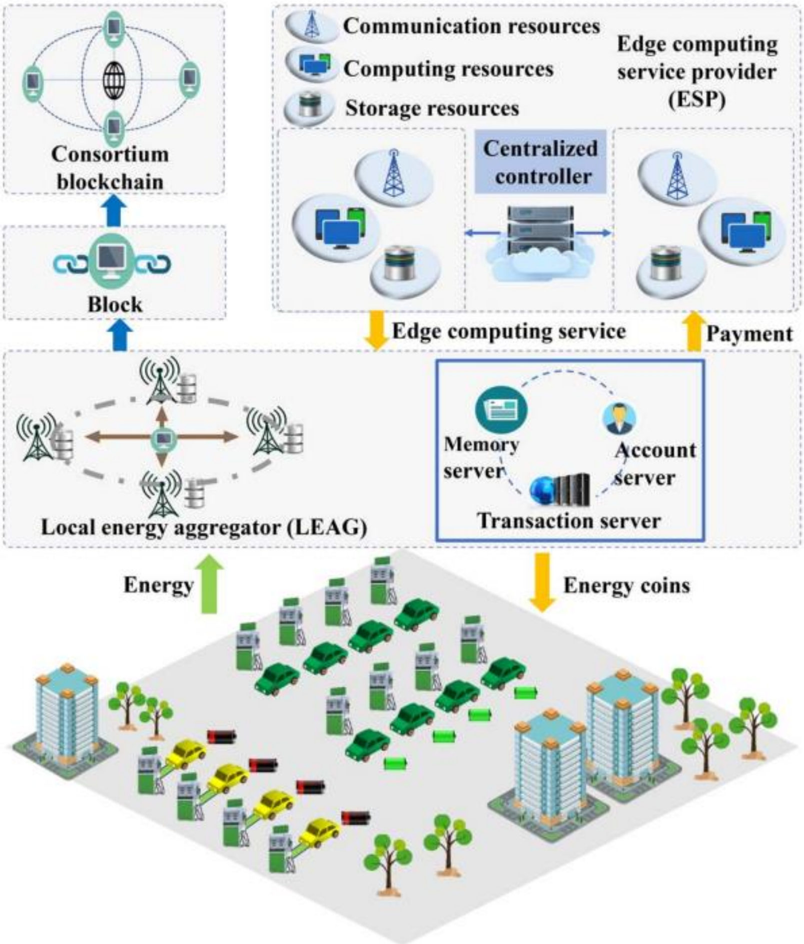


Figure 35. Consortium blockchain-based secure energy trading for V2G. Reprinted from ", Secure and Efficient Vehicle-to-Grid Energy Trading in Cyber Physical Systems: Integration of Blockchain and Edge Computing", by Zhenyu Zhou, Bingchen Wang, Mianxiong Dong, and Kaoru Ota. IEEE Transactions on Systems, Man, and Cybernetics: Systems, Volume: 50, Issue: 1, Jan. 2020. Copyright (2020) by title of publisher.

In [41], a data-driven smart grid framework is being proposed focusing on two aspects: energy trading and autonomous vehicle charging (See Figure 36). The framework leverages deep learning, linear optimization, semantic technology, domain-specific modelling notation, simulation and elements of relay protection. The deep learning module together with code generation time and energy distribution cost reduction performed within the simulation environment are being evaluated. The architecture of the system is summarized below:

1: Semantic annotations of adaptation strategy,

2: SPARQL queries and query results,

3: Command parameters,

4: Input data for calculation and its results,

5: Device-specific command script,

6: Voltage/current regulation and turning the devices on/off,

7: Events and messages,

8: Electric and other measurements,

9: Semantic annotations of data analysis results

10: Transaction execution in targeted blockchain

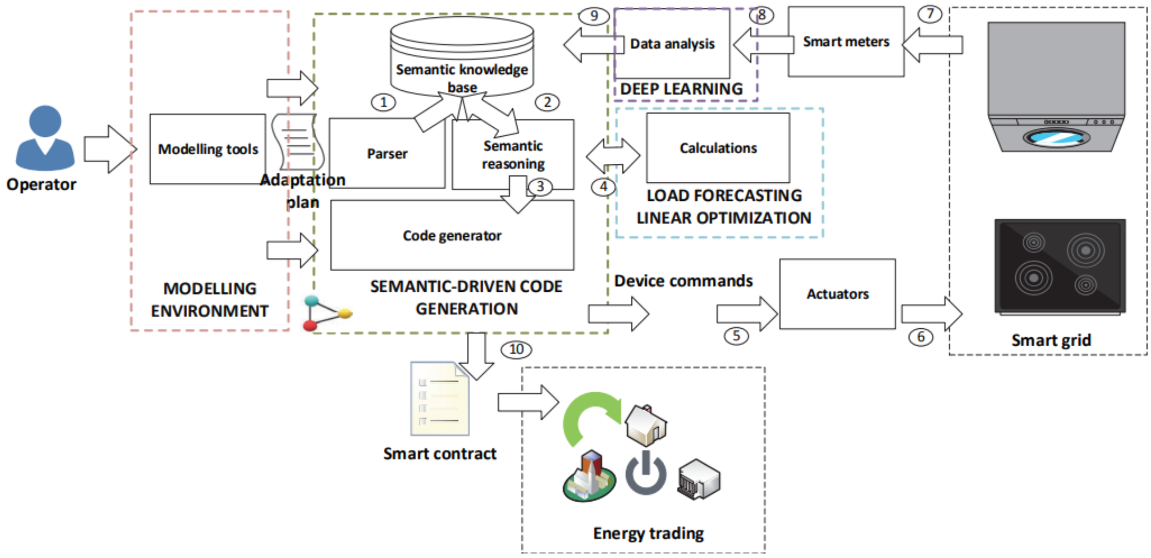


Figure 36. Overview of the data-driven architecture for energy-efficient Smart Cities. Reprinted from "Data-driven framework for energy-efficient smart cities", by Nenad Petrović, Đorđe Kocić, SERBIAN JOURNAL OF ELECTRICAL ENGINEERING Vol. 17, No. 1, Feb. 2020. Copyright (2020) by title of publisher.

Table 5. Comparison of the different features extracted from the Energy trading implementations in Electrical Vehicles literature.

Source	Methodology	Product	Sustainability Perspective
[5]	Architectural development security analysis, simulation testing, performance analysis	A secure and efficient scheme for V2V and V2G energy trading	Social, Economic, Environmental
[10]	Architectural analysis, process design, performance evaluation	A Decentralized Electricity Trading Framework (DETF) between Connected Electric Vehicles (CEVs) in parking lots	Social, Economic, Environmental
[14]	Architectural development, experimental evaluations, computation cost analysis	Blockchain-Based Cyber-Physical Security for Electrical Vehicle Aided Smart Grid Ecosystem	Social, Economic
[19]	Architectural analysis, process design, performance evaluat-ion, security analysis	BlockEV, a blockchain-based efficient Charging Station selection protocol for EVs with smart contract implementation	Social, Economic, Environmental
[37]	Architectural analysis, system modelling, performance evaluation	Vehicle-to-Grid Energy Trading in Cyber Physical Systems: Integration of Blockchain and Edge Computing	Social
[41]	Architectural design, algo-rithm implementation, simulation, performance evaluation	A data-driven smart grid framework focusing on two aspects: energy trading and autonomous vehicle charging	Social, Economic

3.2. ANALYSIS OF IMPLEMENTATION DETAILS

In this section, the technical contributions of the reviewed literature are evaluated, by identifying their underlying blockchain technology, the maturity of their solution, and the quality of their experiments. The sophistication of the implementations and the technologies applied, were used as the assessment tools of the maturity factor.

Blockchain testing, applied by the authors, included: Functional testing of various functional parts of the blockchain (e.g. evaluation of smart contracts), API testing for ensuring that API requests and replies are formatted and handled properly, Performance testing for the identification of possible bottlenecks, Node and shared ledger testing for ensuring the streamlined functioning of the applications.

Test level implementations included the use of automated scripts, command-line interfaces, basic performance tests using test suite tools (Truffle, Ethereum Tester, Populus etc.). More advanced implementations included digital decentralised applications (i.e. DApps) with integrated identity management, enhanced functionalities, third party services [5] and user interfaces to operate with the smart contract.

As noticed in the reviewed literature, the majority of the publications included performance indicators of their proposals in order to:

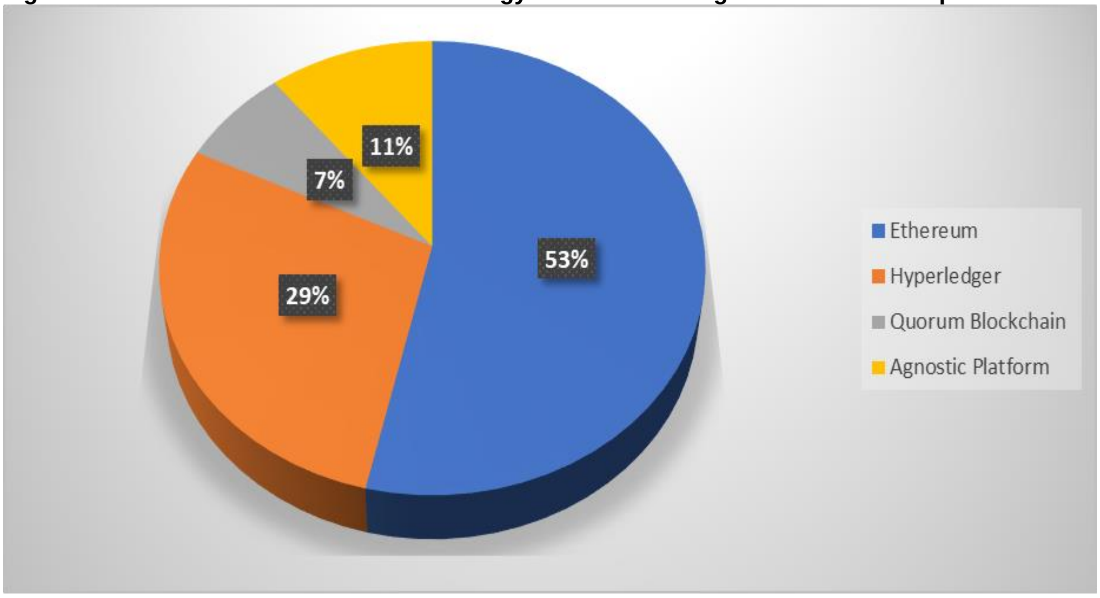
- measure the latency, throughput, network traffic, memory, CPU utilization and fail rate of their transactions
- ensure that provide scalable solutions are provided
- guarantee security, privacy, unforgeability, and verifiability of energy trading data
- ensure fairness of system resource allocation of the proposed blockchain ecosystem
- evaluate the cost of smart contract operations

The majority of the Energy Trading implementations in the literature use Ethereum as the underlying blockchain technology. The main reason for that, lies on the ability to easily write and deploy Smart Contracts. Ethereum is an open source distributed public blockchain network that runs the Smart Contracts on the EVM (Ethereum Virtual Machine) for applications that are attributed to being decentralized and are for mass consumption. It offers great variety of developer tools, while Ethereum wallets (i.e. MetaMask4, Argent5, Rainbow6) provide user-friendly interfaces for Ethereum applications.

The second preferred technology is Hyperledger, a global enterprise permissioned blockchain project. The core idea of the Hyperledger Fabric is to be able to build a customized modular architecture. Thus, administrators can choose the consensus they need, the actors and entities who can read/write blocks etc. Since all the peers are nominated by the administrators in the blockchain, and since all the peers have a business interest to participate to the blockchain, there is no need for gas to makes things running. That's a big difference between the Ethereum and the Hyperledger Fabric. With Hyperledger Fabric there is no need for any kind of cryptocurrency to run the smart contracts and handle transactions. A few cases in which Hyperledger Besu, Hyperledger Burrow and Hyperledger Caliper were used also appear in bibliography.

Another technology that is used in the literature is the Quorum Blockchain [15], [16], an open source blockchain protocol, derived from Ethereum by modifying the Geth client. It is specially designed for use in a private blockchain network, where there is only a single member owning all the nodes, or, in a consortium blockchain network, where each member owns a portion of the network. Finally, Antchain, a blockchain-as-a-Service (BaaS) technology derived from China, also appears in bibliography [3]. As depicted in Figure 4, the majority of the papers provided test-level implementations (mostly using Remix platform). In addition to the aforementioned blockchain technologies, there is also one ad-hoc implementation using Python [30], and another one using Oyente [5].

Figure 37. Blockchain use cases in the energy sector according to the blockchain platform used



According to the statistics, only 28 out of the 63 papers (i.e. approximately a 44%) included an analysis comparing their methods with state of the art by using mainly descriptive methods, as well as and/or metrics in few of the cases (i.e. in [24] [26]). This lays significantly on the lack of standardized benchmarks, that could be used validate such platforms as well as in the extensive homogeneity in the implementation in terms of programming languages used.

The blockchain activities were classified, according to the consensus algorithms used, wherever this information has been made publicly available. The most common consensus mechanisms found in the citations were Proof-of-Work (PoW), Proof-of-Stake (PoS), and Practical Byzantine Fault Tolerance (PBFT). The consensus algorithms categorized as “Others” include, among others, Tendermint BFT, HLF, Clique, and Raft.

Proof of Work (PoW), which was initially used in Bitcoin, achieves consensus proof by solving a difficult problem, that is, by forming a hash value satisfying the condition. Double-spending can be avoided to some extent because, although finding an answer requires a lot of computing resources, it is easy for other nodes to verify the answer. Its weaknesses are obvious, such as the long delay to confirm a trade [77]. The main issue of PoW in Bitcoin is, however, that it cannot be directly used for energy transactions, because it only provides integrity check for things, which is far from enough for energy transactions [78]. In the literature, improvements are being provided, via the auction-based market model, via the two pricing models for uniform and discriminatory pricing schemes and via cloud computing schemes as a solution for miners to outsource computing resources to cloud computing servers. Another improvement in citations using PoW was to authorize only a portion of the nodes for the consensus process together with a credit-based payment mechanism designed to reduce the transaction confirmation time.

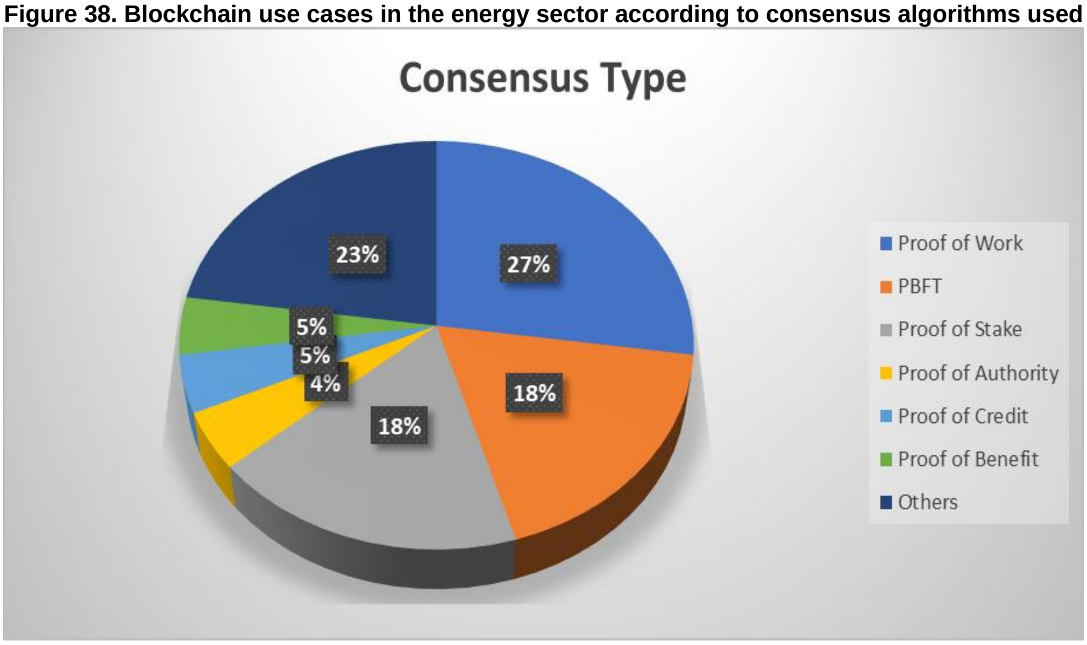
Proof of Stake (PoS) requires little CPU power. In the proof-of-stake system, instead of competing, miners maintain a set of validators that participate in the block creation process. Each verifies that it has a stake in the grid, and the equity is used to determine the likelihood that the node adds the next block of transactions to the blockchain. The system requires participants to prove the ownership of the currency. People with more money are less likely to attack networks. However, this mechanism tends to make the rich richer and the poor poorer. POS has not been widely applied in the actual energy system model design. However, in some of the citations, the demand response program is verified based on the POS consensus mechanism. Each distributed energy prosumer in the grid can act as an energy transaction verifier and can be the next effective block miner, and each verifier holds a certain stake.

The practical Byzantine fault-tolerant algorithm is a replication algorithm suitable for small networks, consortium blockchain or private blockchain. The consensus process requires three rounds of voting and each of which is broadcast; each node needs to know the identity of every other node in the network. Because it does not have the same mining process as PoW, it saves a lot of energy. The right consensus can be reached when the number of malicious nodes is less than one-third of the total number of nodes. The Hyperledger Fabric uses PBFT to reach consensus.

Proof-of-Authority (PoA) is a consensus mechanism used also in consortium blockchain and in private blockchain. Nodes with particular keys hold the state of the validator, and only the validators are allowed to add blocks on the chain, acting as a set of authorities to create and protect the chain. In comparison, PoA it has lower latency, less computation, and is more secure.

Tendermint is another consensual mechanism based on the Byzantine general problem. After each round of broadcasting a block, the validator selects whether to broadcast the pre-vote on the proposed block. If more than two-thirds of the nodes agree, then the submission of the block is broadcast by the validator. Thus, similar to PBFT, all nodes must be known, but it can provide more stringent guarantees. A node must lock its coin to become a verifier. If it is dishonest, it will be punished.

Figure 38. Blockchain use cases in the energy sector according to consensus algorithms used



Finally, the challenges and limitations related to blockchain technology and the implementations' outcomes provided by such works are being presented. As primary concerns by the majority of the authors, are mentioned issues related to performance (e.g., latency of transactions, throughput etc). The cost of deploying smart contracts and transactions, which has an impact on public blockchain systems like Ethereum, is also being extensively discussed. Other challenges include implementation issues, due to the maturity of the technology, scalability challenge and computational complexity of the decentralized algorithms in order to support large-scale IoT networks, as well as the lack of a proper regulatory framework and standards, which impedes the roll-out of similar solutions in the energy sector.

4. Discussion for Future Challenges

Based on the analysis described in Section 3, the main points regarding the open issues and challenges of current blockchain-enabled Energy Trading implementations are being highlighted below, along with areas of focus for future work. Additionally, the key findings of the literature overview are being outlined concerning the research key axes initially introduced.

4.1. OPEN ISSUES AND CHALLENGES

Although blockchain-based energy trading has been a popular research topic, with new blockchain architectures, models and products being continually introduced to overcome the limitations of existing solutions, there are still some dimensions to be optimized. In this section, these challenges and limitations in blockchain-based energy trading are identified and summarized. Some of the potential issues briefly stated in the citations retrieved are the following:

i) Low efficiency and high transaction costs. Due to the shortcomings of blockchain, the transaction speed cannot meet the system requirements, while the transaction costs of blockchain can raise the overall cost of the system.

ii) Privacy protection and security issues [4,16]. There may exist a possible unfairness between energy trading partners, prone to unfair or malicious behaviour from energy buyers or sellers. The rights and interests of both parties in the transaction need to be guaranteed.

iii) Real-time communication. There may exist a challenge for the real-time communication of a large amount of sensor data. While 5G network connectivity is available, it is highly concentrated in the more urban provinces of the country. Most of the countries are either being serviced using 3G and 2G connectivity or being without network connectivity. Microgrid communications would therefore need to be able to operate on limited bandwidth while also being able to continue and recover should there be an interruption in the connection.

iv) The pricing model. A deal must be priced properly in a way to help buyers and sellers reach an agreement quickly.

v) Cost minimization, welfare maximization. In the case of multiple variables, how to ensure the minimization of the overall energy cost of the system, as well as the assurance of trust, rationality of independent individuals, and computational efficiency must be considered.

vi) There is also the issue of environmental energy consumption, because the system requires a large carbon footprint.

The main however issues that may pose a general concern regarding the practicability of energy trading applications are analysed below.

Working prototype testing pilots: Most citations in literature only simulate the relevant functions at the level of blockchain platform without connecting it with an actual physical system so as to realize the synchronous operation of an integrated energy market service in the combined physical, information and market layers. Only some organizations are currently involved in real-world pilot studies for adopting blockchain in Energy Trading (as it is stated in Chapter 1 and in some citations included in the reviewed literature [i.e. [4]). Thus, despite these pilot initiatives exhibiting the potential of blockchain energy trading solutions, in terms of transparency, verifiability and reduced transaction costs, still the capabilities of blockchain to deliver real business value are not clearly defined. A full-scale deployment is required, including real-life scenario tests, different cost pools and operational requirements, in order to evaluate the robustness of the blockchain business venture.

In terms of real-world testing solutions, there is also a high barrier to technology and process adoption. Certain consumers may be hesitant to accept blockchain-based Energy Trading solutions due to a lack of knowledge and comprehension of the technology. As the size and complexity of the system grows, upgrading to large distributed systems becomes more complicated. In real-life Energy Trading scenarios, complex operational processes and individuals with competing interests exist. It is unlikely that the existing energy infrastructure in Europe and at the national level would currently be able to absorb a massive flow of blockchain projects. The energy network in Europe continues to struggle to integrate a growing number of renewable energy and storage systems. Therefore, the practicability and feasibility of blockchain-based energy trading solutions should be verified across all participants taking into account end-to-end approaches.

Blockchain technological challenges: In terms of performance, parameters such as transaction latency and throughput which affect scalability are critical to ensuring the operability of the blockchain solutions. The selection of the proper blockchain architecture (e.g. public blockchain, private blockchain, and their permission management) is crucial. Research efforts on distributed consensus algorithms, which are crucial to achieving these objectives, are still ongoing, however a solution that combines all desired characteristics cannot yet be achieved without significant trade-offs. PoW algorithms are more mature and secure, but on the other hand are also slow and very energy intensive. As a result, blockchain developers are increasingly moving towards PoS schemes that are energy efficient, faster and more scalable. Yet, this move may come with a number of functional limitations, therefore it must be carried out with caution. Other promising solutions include techniques such as 'sharding' that enable parallel processing, (sharding is a method for distributing a single dataset across multiple databases, which can then be stored on multiple machines. This allows for larger datasets to be split in smaller chunks and stored in multiple data nodes, increasing the total storage capacity of the system). Often these solutions may come, however, to the expense of security and decentralisation. Several recent developments, such as the Energy Web blockchain, can be scaled up to thousands of transactions per second. Furthermore, the development and deployment of efficient and secure smart contracts and data management procedures (e.g. decentralized data storage in cloud aiming to the minimization of on-chain data storage) still remain a challenge.

Privacy and security risks are quite likely to arise as a result of poor system design or malicious assaults. Due to a lack of experience with large-scale applications, blockchains face additional risks, such as possible malfunctions in the early stages of development. Blockchain ecosystems rely heavily on coding new algorithms, a procedure that can be prone to errors. Consumer scepticism and delays in adoption could be caused by security gaps before the technology matures. Regarding cyber-attacks, Bitcoin, the oldest blockchain implementation, has proved to be relatively resilient, but other platforms such as Ethereum, have been the target of serious attacks in the past. Unfortunately, vulnerabilities in terms of cyber-security often come from peripheral applications, such as digital wallets or smart contracts. Resilience to such attacks is of great importance, especially for applications in key infrastructure, such as energy systems.

Benchmarking of ET applications: From the retrieved literature, the lack of standardized benchmarks [17Scopus] to compare different blockchain implementations is evident, especially in terms of different hardware, software and transaction settlements. Most studies provide experimental results of the performance and scalability of their solutions in terms of transactions per second, throughput of the proposed framework with different send rates of transactions and/or with varying number of nodes, as well as the approximate cost in terms of gas fees. However, few papers provide the smart contract code or a security/privacy analysis [6,15,19,20,24,32,47,52,53]. Several, more may provide the algorithmic implementation of the proposed energy trading framework [16,20,33,41].

Sustainability concerns: Throughout the literature review, it wasn't easy to identify blockchain-based energy trading solutions' economical, environmental, and social impact. The sustainability perspective was implied/cited in all selected papers but not thoroughly stated. For example, it’s not clear how a company can meet the expectations of various stakeholders concerning societal priorities (including its customers). Additionally, environmental-related concerns are significant, given the massive energy requirements of current blockchain networks. Also at an economic level, real-life testing is needed to assess the potential of blockchain technology to minimize operational costs. Especially due to the fact that all papers’ cost analysis was about blockchain-related costs (gas fees, etc.) and not about the economic benefits from actually adopting the blockchain technology in energy trading implementations.

Investment and operational costs: Despite its efficiency and capacity to reduce transaction costs, blockchains remain an energy- and time-intensive technology: Ethereum, for example, uses 5 TWh/year, and each transaction costs 30 cents. Minting cryptocurrency requires high performance computers and a lot of power. This fact leads to high development costs. Blockchains may realise significant cost savings by circumventing intermediaries, however, blockchain systems may require costly new infrastructures, such as custom ICT equipment and software, the costs of which need to be outweighed by benefits achieved by data integrity, enhanced security and elimination of the need for a trusted intermediary. Building blockchain applications entails high costs since it incurs various design, development, deployment, migration and maintenance costs. Blockchain integration with existing Enterprise Resource Planning (ERP) systems necessitates substantial financial commitment. On-boarding and maintenance expenses are also significant. Suppliers, third-party logistics providers, distributors, and manufacturers who participate in an Energy Trading network will be responsible for the cost of hosting a node (energy spent) inside a blockchain consortium. High costs will be incurred in the form of maintenance, data storage, and infrastructure improvements as a result of high volume transactions over broad networks. In the energy sector, smart meters are currently being rolled out without significant computational capabilities, hence integrating the existing smart metering and grid infrastructure with distributed ledgers could come with significant costs. All the above may lead investors to think they might not have the competitive advantage against already existing solutions in well-established markets.

Addressing the "garbage in, garbage out" challenge: Using robust identity management frameworks to preserve the veracity of data submitted as an input in each specific blockchain application could be part of the solution. Since blockchain networks cannot guarantee the veracity of data that was not natively generated on-chain (such as information coming from IoT devices), future research should focus on innovative ways to secure the source of generated info and the veracity and integrity of data across Energy Trading networks.

Complexity challenges for “small” consumers: Managing contracts with other participants and running production, storage and energy-using facilities is a very complex process for most users who have little interest in their power supply. This complexity may also limit the consumers’ trust in an invoicing system where the amount to be paid would no longer be based on consumption read on the meter applied to the tariff given by the energy supplier. Finally, participating in a local energy marketplace may expose "small" consumers to intolerable price risks.

Regulatory challenges of blockchain: Significant barriers in the adoption of the technology are relevant both to the lack of flexibility in the regulatory and legal sphere. Regulatory bodies endorse the active participation of consumers in electricity markets. In addition, several policy makers have established supportive measures for local or community energy systems with the goal of lowering consumer costs and promoting low-carbon technologies. Blockchain technologies can support or accelerate such objectives, therefore coordinate well with current regulatory priorities, however regulatory frameworks would need to be amended to allow larger adoption of DLT. New contract types will be required to describe agreements between prosumers and consumers, especially when counterparties make use of the public grid. The most essential aspect of a new framework is that it would necessitate new and potentially more flexible electricity tariffs, which are currently heavily regulated. In general, local or microgrid energy markets would need to be integrated with current regulatory practice. Despite initial efforts towards standardization of blockchain technology (e.g. ISO/TC 30715), there is a way to go, especially given the legal constraints that come with implementing such a system.

Pilot projects to test such novel marketplaces have been granted special clearance by regulatory bodies to evaluate possible benefits for consumers and energy system operation. Blockchain technologies have begun to show their value in decentralized microgrids, but they confront hurdles in terms of balance, integration, and coordination with the main grid. Energy trading needs to be harmonized with the system operator practice, and decentralization may lead to more complex management of energy systems overall. P2P marketplaces and local microgrids may even accelerate grid defection or lead to severe underutilization of network assets. All of these challenges necessitate considerable regulatory reforms, which might cause blockchain implementation to be delayed or even halted.

In addition, regulatory authorities are responsible for setting the rules of consumer data protection such as the GDPR EU policy on consumer data. Blockchain system users should comply with their liabilities but at the same time, consumer sensitive information needs to remain confidential, such as the prices agreed between an energy supplier and consumer within a smart contract recorded in a ledger. When information from numerous participants is recorded in shared ledgers, data privacy, confidentiality, and identity management solutions must be discovered. Furthermore, smart contracts must be incorporated into legal code to ensure compliance with the law and consumer protection. It's not always apparent who bears legal and technical responsibility for the negative repercussions of diverse parties' actions in a distributed system architecture. Trust is put to the technology itself rather than in a known authority.

Standardization and certification of blockchain-enabled Energy Trading process: Finally, another significant factor that might slow blockchain adoption is the lack of standardization and flexibility. To allow interoperability amongst technology solutions, standards for blockchain architectures must be defined. Another issue is that once a blockchain system is deployed, any modifications in the ruling protocols or code needs to be approved by the system nodes. In blockchain ecosystems, this has historically led to disagreements between developers and multiple system forks. These issues may lead to mistrust and fragmentation if blockchains are widely adopted in energy systems [48].

4.2. KEY FINDINGS

In the sequence, a summary of the main findings of the thesis is provided in accordance with the various key axes initially posed.

KA1: The available blockchain-enabled Energy trading implementations encompass the domains of smart grid and electrical vehicles (EVs). The majority of the retrieved blockchain implementations, however, fall within the smart grid domain. The list of energy trading products includes, among others, a cloud service platform of energy market, a Private Energy auction for blockchain microgrid system and a public blockchain-based pricing scheme. All authors cited the architecture development as well as system design/testing methods according to the methodologies applied. Furthermore, many authors included simulations as their main testing methodology. Finally, many authors applied a cost-benefit and a security analysis. Regarding the maturity of blockchain implementations many milestones have been overcome, however still integration, scalability and benchmark-related issues discussed in Section 4.1 need to be further addressed.

KA2: As stated in Section 3.2, most implementations are not completed with advanced and functional interfaces. This, in combination with the lack of benchmarking and testing in large scale under real conditions, makes evaluating the quality of offered solutions difficult. When it comes to the underlying blockchain technologies, the Ethereum blockchain is the most used, followed by Hyperledger.

KA3: As stated in Section 4.1, despite the sustainability perspective of their solutions, that the authors claim in their works, it is difficult to assess the positive impact on economic, environmental and social welfare, since most authors concentrate on the performance of the architecture proposed. However, the regulatory obstacles as well as the inherent technological issues of blockchain technology, constitute a significant burden. A systematic approach to evaluating the various sustainability aspects will make a positive impact on advancement of the state of the art.

KA4: Enhancing the maturity of implementations and the quality of the performance evaluations will contribute in a more holistic view of how a blockchain system would perform in real-life Energy Trading scenarios. Lack of regulations and benchmarks impede researchers and practitioners from developing and testing complete blockchain-based solutions. All these aspects need to evolve in parallel, towards offering a solid paradigm for the transition and adoption of blockchain.

5. Conclusions

Industry stakeholders, utility companies and energy decision-makers have shown a great interest in blockchain technologies. Trials, pilot projects and novel business models have emerged from the use of the Blockchain technology in the energy industry. Several applications are being developed such as wholesale energy trading, platforms that provide end-consumers with access to wholesale energy markets, and P2P energy trading platforms between prosumers/consumers. In this thesis, a systematic literature review of the available blockchain-enabled Energy Trading implementations was presented. Based on a thorough classification scheme (including the platform and consensus algorithms used), a taxonomy of the various blockchain-related energy trading systems across Smart Grid and Electric Vehicles domains was presented, with a specific focus on their sustainability features.

Special attention was given to the maturity and technical features of the available energy trading implementations, especially in terms of blockchain platforms used and their implementation status. The proposed blockchain-related energy trading solutions cannot achieve clear economic, environmental, or social objectives, according to the selected literature's sustainability viewpoints. The majority of the articles present test-level implementations utilizing relevant test suites, mainly the Ethereum and Hyperledger (Fabric) blockchain platforms.

Although blockchain based energy trading approaches are continuously gaining ground, a lot of technical, organizational and regulatory issues remain unaddressed, such as the scalability of the available platforms, throughput, data privacy and identity management, grid destabilization and blockchain-associated legal issues, whilst the lack of standardization adds to the prevalent interoperability issues. The challenge of balancing demand and supply is one that blockchain systems cannot solve on their own. To resolve such issues, a mix of artificial intelligence (AI), machine learning, and predictive analysis would be necessary. In conclusion, the up-to-now unstructured experimentation of blockchain-related energy trading solutions on behalf of the researchers, need to be oriented towards the development of test real-life implementations, especially considering their ability to create added value to energy cost-related aspects.

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