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Directeur de thèse: **M. Daniel KOFMAN**

Jury

M. Georg CARLE, Professeur, TU München, Allemagne	Rapporteur
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Mme. Ana BUŠIĆ, Chargé de Recherche, Inria, France	Examinatrice
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M. Philippe FUTTERSACK, Chef de groupe, EDF R&D, France	Invité
M. Daniel KOFMAN, Professeur, Télécom ParisTech, France	Directeur de thèse
M. David MENGA, Chercheur, EDF R&D, France	Encadrant industriel

TELECOM ParisTech
école de l'Institut Mines-Télécom - membre de ParisTech
46 rue Barrault 75013 Paris - (+33) 1 45 81 77 77 - www.telecom-paristech.fr

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José Horta

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Innovative paradigms and architectures for future distribution electricity networks supporting the energy transition

PhD Director: **Daniel KOFMAN**
Industrial advisor: **David MENGA**

A mi esposa,

A mis padres y mis hermanos,

A mi abuelo Doly.

Abstract

Future electricity distribution grids will host an important and growing share of variable renewable energy sources and local storage resources. Moreover, they will face new load structures due for example to the growth of the electric vehicle market. These trends raise the need for new distribution grid architecture and operation paradigms to keep the grid stable and to ensure quality of supply. In addition, these new paradigms will enable the provision of advanced new services.

On the one hand, distribution System Operators will increasingly rely on demand side flexibility provided by distributed energy resources (such as flexible loads, storage resources and controllable distributed energy sources) due to their adaptability and potential cost-effectiveness compared to traditional infrastructure reinforcements. On the other hand, households will progressively become prosumers playing an active role on smart grid energy management by exploiting flexibility potential of household devices that consume, store or produce electricity. The Internet of Things is a main enabler for households to play an active role, as it has been pushing a new wave of Smart Home connected devices and related services, from which the energy domain can become one of the main business cases.

In this thesis we propose a novel architecture capable of fostering collaboration among wholesale market actors, Distribution System Operators and end customers, to leverage flexible distributed energy resources while respecting distribution system constrains. The architecture is designed for providing innovative Residential Demand Side Management services, with a special focus on services enabled by self-consumption at the household and neighborhood level. Following these general objectives, the thesis provides three main contributions. First, based on Internet of Things and blockchain technology, we propose the building blocks for future distribution grid energy management architectures. Then, focusing on the services enabled by such architectures, we propose hour-ahead markets for the local exchange of renewable energy among households together with dynamic phase allocation mechanism to improve the quality of electricity supply. Finally, we propose a real time control mechanism for the adjustment of market decisions to satisfy Distribution System Operator constraints.

The architecture and demand side management mechanisms proposed in this thesis have the potential to alleviate congestion, reduce voltage deviations and losses, and consequently augment distribution grid capacity for hosting renewable energy sources. We evaluate such potential through comprehensive simulations using power flow analysis and realistic load profiles, providing valuable insight for the design of future distribution grid architectures and energy management systems.

KEY-WORDS: Demand Side Management, Smart Grids, Internet of Things, Market Mechanisms, Game Theory

Résumé

Les futurs réseaux de distribution d'électricité devront héberger une part importante et croissante de sources d'énergies renouvelables intermittentes. De plus, ils devront faire face à des nouvelles variations des courbes de charge, dues notamment à une part croissante de véhicules électriques. Ces tendances induisent le besoin de nouveaux paradigmes et architectures d'exploitation du réseau de distribution, afin de fiabiliser les réseaux et assurer la qualité de fourniture d'électricité. Par ailleurs, ces nouveaux paradigmes vont permettre le développement des services innovants.

D'un côté, les gestionnaires de réseau s'appuieront de plus en plus sur des flexibilités fournies par des ressources énergétiques distribuées (flexibilités de consommation, stockage électrique, modulation des sources d'énergie) à cause de son potentiellement meilleur rapport coût-efficacité par rapport au renforcement des infrastructures. D'un autre côté, les consommateurs deviendront progressivement des prosumers (acteurs de leur consommation d'énergie) qui joueront un rôle actif dans la gestion de l'énergie des réseaux intelligents, en exploitant la flexibilité de certaines des équipements de leur logement (appareils électroménagers, batteries et panneaux solaires) pour moduler leur courbe de charge. L'Internet des Objets est un outil essentiel pour permettre aux logements de jouer un rôle actif, car il a poussé une nouvelle vague d'appareils connectés à la Smart Home et de services associés, dont le domaine de l'énergie peut devenir l'une des principales applications.

Dans cette thèse nous proposons une nouvelle architecture capable de favoriser la collaboration entre les acteurs du marché de gros, les gestionnaires de réseau de distribution et les clients finaux, afin de tirer parti des ressources énergétiques distribuées tout en prenant en compte les contraintes des réseaux de distribution. L'architecture est conçue pour fournir des services innovants de gestion de la demande résidentielle, avec un focus particulier sur les services liés à l'autoconsommation individuelle (au niveau d'un logement) et collective (à l'échelle d'un quartier). Dans le cadre de ces objectifs généraux, la thèse apporte trois contributions principales. D'abord, sur la base de l'Internet des Objets et de la technologie blockchain, la thèse fournit les éléments de base pour les futures architectures de gestion de l'énergie au niveau du réseau de distribution. Ensuite, en focalisant sur les services rendus par de telles architectures, nous proposons un marché intra-journalier au pas horaire pour l'échange local de l'énergie renouvelable entre les logements, associé à un mécanisme d'allocation dynamique des phases afin d'améliorer la qualité de fourniture d'électricité. Finalement, nous proposons un mécanisme de contrôle en temps réel pour l'ajustement des transactions du marché vers des échanges finaux d'électricité qui respectent les restrictions posées par le gestionnaire du réseau électrique.

L'architecture et les mécanismes de gestion de la demande proposés visent à réduire les transits et les pertes et, par conséquent, à augmenter la capacité d'accueil des sources d'énergie renouvelables sur les réseaux de distribution basse tension. Les performances sont évaluées à l'aide de simulations de load flow basées sur des profils de charge réalistes. Elles fournissent des éléments utiles à la conception des futurs systèmes de gestion des réseaux de distribution.

MOTS-CLEFS: Gestion active de la demande, réseau électrique intelligent, Internet des Objets, Mécanismes d'enchères, Théorie de Jeux

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Résumé en français

1 Introduction

Le réseau électrique est l'un des systèmes le plus complexes a avoir été construit par l'homme et il est destiné à continuer à l'être pendant que nous évoluons vers les *Smart Grids* (réseaux électriques intelligents) dans le contexte de la transition énergétique.

La réduction des émissions de CO2 et l'indépendance énergétique sont deux des principales objectives de la Communauté Européenne en termes de transition énergétique. Le déploiement massive de sources d'énergie renouvelable intermittentes et des véhicules électriques sont les moyens le plus importantes pour atteindre ces objectives. Ces tendances induisent le besoin de nouveaux modèles d'exploitation des réseaux électriques, lesquels n'ont pas été conçus pour accueillir les dites ressources. Au fur et à mesure que la production devienne intermittente et que la visibilité sur le comportement de la consommation se réduit, les gestionnaires des réseaux électriques devront s'appuyer de plus en plus sur la Gestion Active de la Demande (Demand Side Management (DSM)), afin de fiabiliser les réseaux et différer les coûts de renforcement des infrastructures.

DSM est un vaste concept qu'inclut des programmes d'amélioration de l'efficacité énergétique des installations, des appareils électriques et des comportements de consommateurs, et des programmes de Demand Response (DR), dans lesquels des technologies de l'information et la communication sont déploies pour avoir un contrôle/influence sur des flux électriques échangées par les clients avec le réseaux électrique pendent certains périodes de temps. En exploitant la flexibilité et un usage efficient des ressources énergétiques reparties (flexibilités de consommation, stockage électrique, modulation des sources d'énergie) en échange des incitatifs appropries pour les propriétaires des dites ressources, DSM et en particulière les programmes de DR ont un grand potentielle pour aider les réseaux électriques à affronter les défis posées par la transition énergétique.

D'un autre côté, les consommateurs deviendront progressivement des prosumers (producteurs-consommateurs et acteurs de leur consommation d'énergie) qui joueront un rôle dans la gestion de l'énergie des réseaux intelligents, en modulant la consommation des équipements de leur logement (appareils électroménagers, batteries et panneaux solaires). Pour faciliter une telle participation, des technologies avancées de communication et de contrôle sont nécessaires, mais le processus de définition de politiques d'utilisateur et tout autre interaction avec les clients doivent être simples et peu nombreuses. L'Internet des Objets (Internet of Things (IoT)) a poussé une nouvelle vague d'appareils connectés à la Smart Home et de services associés, dont le domaine de l'énergie peut devenir l'une des principales applications. L'IoT, applique suivant des principes de systèmes autonomiques, est un outil essentiel pour permettre aux logements de jouer un rôle actif dans la gestion énergétique tout en ayant un impact minimal sur le confort des clients.

Un nouveau cadre réglementaire ainsi que des nouveaux marchés et modèles business doivent être conçus pour favoriser la participation active des clients et pour permettre le développement des services énergétiques avancées liées à la DSM, au comptage intelligent de l'énergie, à l'automatisation des réseaux électriques de distribution, à des systèmes de gestion de crise, etc. Notre travail se focalise sur les services liées à la DSM, en particulière appliquées à la gestion des flux d'énergie dans une réseaux électrique de distribution. Les réseaux électriques de distribution et les locaux du client (résidentielle, commerciale et industriel) sont les domaines où la plus partie de défis vont apparaitre, principalement à cause du déploiement des panneaux photovoltaïques sur les toitures des clients, et où la communauté des technologies de l'information et la communication peut apporter le plus de valeur ajouté.

Cependant, les flexibilités de consommation sont aujourd'hui essentiellement exploitées sur les marchés de gros, tels que le marché de capacité et les marchés de l'énergie (spot et intra-journalier) ainsi qu'au mécanisme d'ajustement, lesquels ont été adaptées pour que les différents acteurs, incluant le gestionnaire du réseau de transport (RTE) et des agrégateurs[1], puissent consommer ou offrir des produits basées sur la DSM et en particulière sur l'effacement de la consommation électrique. Une nouvelle architecture est donc nécessaire pour favoriser la collaboration entre les acteurs du marché national, les gestionnaires de réseau de distribution, les agrégateurs de flexibilités et les clients finaux, afin de tirer parti des ressources énergétiques distribuées flexibles tout en respectant les contraintes des réseaux de distribution.

L'objectif de la thèse est de concevoir une architecture basée sur l'IoT, pour fournir des services innovants de gestion de la demande résidentielle, avec un accent particulier sur les services liés à l'autoconsommation photovoltaïque individuelle (au niveau d'un logement) et collective (à l'échelle d'un quartier). La thèse fournit dans sa première partie les éléments de base pour les futures architectures de gestion de l'énergie dans les réseaux de distribution. La deuxième partie porte sur les services rendus par des architectures basées sur un marché d'échange d'énergie entre les logements, associé à un mécanisme flexibilité en quasi temps répondant aux besoins du réseau de distribution. Les mécanismes de gestion de l'énergie proposés dans cette thèse visent à réduire les transits et les pertes et, par conséquent, à augmenter la capacité d'accueil des sources d'énergie renouvelables sur les réseaux de distribution. Les performances sont évaluées à l'aide de simulations de *load flow* basées sur des profils de charge réalistes. Elles fournissent des éléments utiles à la conception les futurs systèmes de gestion des réseaux de distribution.

Les contributions de cette thèse sont présentées en commençant par un résumé des éléments de base d'une architecture générale basée sur l'IoT pour permettre le développement des services énergétiques dans le domaine résidentielle (Chapitre 2 du mémoire). Ensuite, dans la Section 3, nous abordons la conception d'une architecture pour la gestion d'énergie au niveaux du réseau électrique de distribution en proposant des nouveaux concepts tels que les Réseaux de Distribution Virtualisés (*Virtual Distribution Grids* (VDG)) et les plateformes transactionnels basées sur la technologie blockchain (Chapitre 3 du mémoire). L'architecture décrite nous permet de proposer trois services énergétiques innovants (présentés dans les Chapitres 4, 5 et 6 du mémoire), dont la Section 4 traite sur les transactions d'énergie entre clients résidentiels à travers un marché local visant à équilibrer la production d'énergie renouvelable du quartier avec la flexibilité de la demande. Nous proposons un mécanisme d'enchères et des tarifs de transport dynamiques qu'incitaient les maisons à contrôler leur flexibilité d'une façon qui leur reporte des bénéfices économiques, mais qui bénéficie aussi l'opérateur du réseaux électrique de distribution (Distribution System Operator (DSO)). La Section 5 propose comme deuxième service, l'allocation dynamique de maisons à des phases électriques, en fonction des résultats du marché local d'énergie, visant à résoudre le problème de déséquilibre du réseau de distribution. Le troisième service, proposé dans la Section 6, aborde la mise en œuvre des

[1]Nouveau rôle dans les marchés d'énergie qui peut être joué par les fournisseurs d'électricité ou par de tiers, en charge de gérer la flexibilité de la demande chez les prosumers et de l'agréger pour construire des offres de marché.

transactions du marché local en présence des erreurs de prévision. Nous proposons un modèle basée sur la théorie de jeux pour le contrôle en temps réel des flux électriques des maisons afin de respecter les contraintes du DSO par rapport aux niveaux de tension et des courants sur le lignes. Finalement, la Section 7 présente les conclusions et perspectives correspondant au Chapitre 7 du mémoire de thèse.

2 Architecture *Smart Home* basée sur l'IoT

Dans cette section, nous proposons les éléments de base fonctionnels et technologiques pour la mise en œuvre d'une architecture générale de l'IoT destinée à fournir des mécanismes de DSM résidentiels et des services énergétiques connexes. L'architecture est basée sur une vue d'ensemble des protocoles et technologies supportant la maison intelligente basée sur l'IoT. L'architecture proposée aborde certains des principaux défis rencontrés par les solutions IoT, avec un accent particulier sur les problèmes d'interopérabilité, le manque d'orchestration parmi les contrôleurs et les modèles d'affaires associés.

Afin de structurer notre approche pour construire une architecture générale de bout en bout, nous considérons trois couches architecturales : fonctionnelle, physique et de communications. L'architecture fonctionnelle vise à identifier et synthétiser les moyens par lesquels les services dans la maison intelligent apportent de la valeur aux utilisateurs, l'architecture des composants aborde les technologies permettant le déploiement de ces fonctionnalités sur le terrain et l'architecture des communications décrit les protocoles permettant les interactions entre les appareils et entre appareils et les utilisateurs.

2.1 Architecture Fonctionnelle

Dans une architecture IoT, il existent trois groupes fonctionnels fondamentaux. Le premier groupe est l'ensemble des fonctions à la périphérie de l'architecture, permettant la fusion entre le monde physique et le numérique. Ces *Edge Functions* (EF) peuvent être divisés en détection de l'environnement, action sur l'environnement et interaction avec l'utilisateur. Le deuxième groupe représente les fonctions liées à la gestion et au traitement des données, en fonction des applications qui exécutent la logique métier pour fournir la valeur client. Nous appelons ce groupe *Cloud Functions* (CF), comme pour la plupart des produits et services IoT actuels, ces fonctions sont implémentées sur le cloud[2]. Le dernier groupe fonctionnel, appelé *Networking Gateway Functions* (NGF), est en chargé de permettre l'interconnexion entre les groupes de fonctions EF et CF, en fournissant les fonctions tels que connectivité, interopérabilité, découverte de dispositifs et de ressources, sécurisation des communications, etc.

Ces groupes fonctionnels peuvent être implémentés de différentes manières, à différents niveaux de l'architecture. Dans les sections suivantes, nous analysons les options technologiques pour implémenter l'architecture fonctionnelle dans des composants physiques et pour permettre la communication entre eux.

2.2 Architecture Physique

Implémentation des *Edge Functions*

L'ensemble des objets abstraits pertinents implémentant EF sont des capteurs, *Beacons* et Radio Frequency Identification (RFID), fournissant une information de contexte, des actionneurs, permettant la gestion d'état de l'appareil, et des objets User Interaction (UI). Ces types d'objets sont généra-

[2]Pour le cloud, nous comprenons la virtualisation des infrastructures physiques et leur découplage par rapport à la localisation géographique. Le cloud représente des capacités de stockage et de traitement distribuées pouvant être implémentées à différents niveaux de l'architecture

lement mis en œuvre en tant que dispositifs alimentés par batterie ou en utilisant des techniques de récupération d'énergie pour éviter les coûts et le fardeau de la substitution de la batterie.

Les dispositifs de récupération d'énergie sont basés sur des capacités matérielles extrêmement limitées, spécialement conçues pour les caractéristiques de récolte d'énergie et le code est exécuté directement sur le *firmware*. Les objets abstraits qui peuvent être mis en œuvre en utilisant des technologies de récupération d'énergie sont pour la plupart des balises passives, des capteurs et des simples UI (commutateurs sans fil piézoélectriques, thermostats à énergie solaire, etc.). Les principales technologies fournissant des capacités de récupération d'énergie aux dispositifs périphériques sont EnOcean et RFID.

L'alimentation par batterie est préférés lorsque les exigences d'application ne sont pas adaptées aux contraintes de récupération d'énergie ou pour des objets tels que des actionneurs ou des balises. En termes de matériel, il y a plusieurs plateformes de développement pour le prototypage, telles que Arduino, Zolertia, OpenMote ou encore ARM Mbed. En ce qui concerne Operating Systems (OS) adapté aux périphériques contraints, il existe plusieurs OS légers tels que Contiki, TinyOS, Brillo et RIOT, entre lesquels RIOT montre des caractéristiques supérieures [1].

Implémentation des *Cloud Functions*

Dans les implémentations actuelles de services de type *Smart Home*, la plupart des données et de l'intelligence pour les traiter sont concentrés dans le *back-end*. Cependant, une partie du traitement des données pourrait être distribuée vers la périphérie pour mieux appliquer les politiques de confidentialité des clients, pour éviter les retards dans les applications nécessitant une réponse en temps réel, et pour améliorer la disponibilité en activant des CF en mode hors ligne. La mise en œuvre du *back-end* étant hors de portée de ce travail, nous nous concentrons sur les *Personal Clouds* et les *Smart Objets*, qui représentent des CF implémentés chez les clients. Les *Smart Objets* implémentent une logique métier simple (règles Événement-Condition-Action), tandis que les *Personal Clouds* mettent en œuvre des fonctions plus complexes telles que les mécanismes de prévision, d'optimisation et d'apprentissage. Les *Personal Clouds* reposent sur des processeurs puissants et suffisamment de Flash et RAM pour supporter un OS *full-fledged* et plusieurs applications, tandis que les *Smart Objects* requièrent moins de capacités matérielles et peuvent être implémentés comme applications sur des appareils mobiles ou sur un BeagleBone Black (BBB). En plus des OS *full-fledged*, CoreOS (*Personal Cloud*) et Snappy Ubuntu Core (*Smart Object*) sont mieux adaptés aux environnements IoT.

Implémentation des *Networking Gateway Functions*

Une passerelle physique implémentant la plus partie des NGF serait nécessaire pour optimiser la distribution des données et des intelligences, permettant l'extension des capacités de l'infrastructure cloud à la périphérie. Les exigences pour la mise en œuvre de ce dispositif de passerelle sont centrées sur le support natif pour le *stack* de protocoles, les caractéristiques de fiabilité et de sécurité. Actuellement, il y a des plateformes permettant le développement de passerelles IoT, telles que OpenPi, OpenKontrol Gateway ou BBB avec des extensions de connectivité. En ce qui concerne l'OS, nous considèrerions mbed OS comme le choix principal grâce à son large support des technologies de connectivité, alors que pour Snappy, il y auraient des drivers à développer.

2.3 Architecture de communication

L'architecture de communication consiste en des *stacks* de protocoles qui supportent des interfaces entre blocs fonctionnels, c'est-à-dire parmi des dispositifs/composants physiques mettant en œuvre de telles fonctions. Les EF implémentés par des périphériques contraints représentent l'essence de toute architecture IoT et sont la source des plus grands défis en raison de leurs capacités limitées. Ainsi, nous nous concentrons sur les interfaces incluant des objets avec récupération d'énergie et des dispositifs alimentés par batterie, qui doivent être mis en œuvre par le périphérique de passerelle physique.

Interface avec des objets à recuperation d'énergie

Afin de permettre une autonomie "illimitée", la technologie de communication pour les dispositifs alimentés par récupération d'énergie doit être adaptée aux caractéristiques contraintes du processus de récolte d'énergie, ce qui permet des communications uniquement lorsqu'une quantité d'énergie suffisante est fournie. RFID, Near Field Communication (NFC) (RFID) ou EnOcean sont les protocoles les plus utilisés. Ces technologies définissent une spécification complète dès la couche physique aux profils d'application, incluant la sémantique.

Interface avec des objets alimentés par batterie

En conséquence de la part d'énergie consommée par les émetteurs-récepteurs RF, les appareils alimentés par batterie doivent fonctionner dans des *duty cycles* réduits et les protocoles de communication doivent s'adapter aux périodes de repos où les appareils ne sont pas disponibles. Nous analysons à différentes couches qui sont les protocoles pertinents pour interagir avec ce type de dispositifs.

Technologies de couche de liaison et réseaux - Les deux technologies les plus pertinentes pour la *Smart Home* basé sur IoT sont Bluetooth Low Energy (BLE) et Thread. BLE est le protocole le mieux adapté pour que les appareils personnels communiquent avec des périphériques contraintes à courte distance, pour faire de passerelle, pour un contrôle direct ou pour connaitre le contexte. BLE a une présence consolidée dans les appareils personnels, ce qui reflète sa maturité et son écosystème étendu. Les autres avantages sont : faible coût, faible consommation d'énergie, cadre d'application flexible, protocole de découverte de service et capacités de maillage. Thread est la meilleur implémentation industrielle du *networking stack* IoT (IEEE 802.15.4 PHY & MAC, IPv6 over Low power Wireless Personal Area Networks (6LowPAN), RIP, User Datagram Protocol (UDP) et Datagram Transport Layer Security (DTLS)) pour la communication entre objets. Thread prenne en charge toute couche d'application à faible bande passante s'exécutant sur Internet Protocol version 6 (IPv6), telle que IPSO Smart Objects [2]. Thread permet aux utilisateurs d'ajouter ou de supprimer simplement et en toute sécurité des périphériques sur le réseau et offre une flexibilité et une fiabilité accrues par rapport aux concurrents (Z-Wave et ZigBee).

Protocoles de transport d'application - Le protocole de transport le plus pertinent pour les interfaces impliquant des dispositifs contraints est Constrained Application Protocol (CoAP), un protocole REpresentational State Transfer (RESTful) qui peut être facilement traduit vers Hypertext Transfer Protocol (HTTP). C'est un protocole binaire avec une faible complexité d'analyse et une petite taille de message, ciblant les microcontrôleurs 8 bits à faible coût. CoAP est un mécanisme *request/response* avec support pour *publish/subscribe* (pub/sub) grâce à une extension appelé *Observe*. Les protocoles spécialement conçus pour les fonctions pub/sub, tel que Message Queue Telemetry Transport (MQTT) sont plus adaptés pour les communications asynchrones et *loose-coupled* (collecte de données à partir de capteurs). Il y a MQTT-SN, une version de MQTT pour les réseaux de capteurs, qui s'exécute sur les transports non Transmission Control Protocol (TCP)/Internet Protocol (IP) et s'appuie sur 6LowPAN pour s'adapter aux contraintes des couches de base (MAC/PHY).

Formats d'encodage de données - Les formats de codage binaire, dont Concise Binary Object Representation (CBOR) c'est un exemple pertinent, sont mieux adaptés que ceux basés sur du texte (JSON et XML) pour les périphériques IoT contraints, car ils ont une taille de message plus petite et une complexité d'analyse inférieure. Il existe également Efficient eXtensible Markup Language (XML) Interchange (EXI), un mécanisme de compression de XML, qui est efficace sur le réseau mais nécessite plus de traitement sur les *end points*.

Profils d'application - Les deux protocoles de couche d'application développés spécifiquement pour la gestion de l'énergie sont Smart Energy Profile (SEP 2.0) et OpenADR. Ces deux normes permettent un échange de messages ouvert et interopérable entre des dispositifs fournissant/utilisant des services énergétiques et des fournisseurs, des agrégateurs et des opérateurs réseau. SEP 2.0 est plus axé sur l'intérieur du bâtiment (maison), en modelant des appareils tels que les écrans et les thermostats ; tandis qu'OpenADR se concentre sur les interactions entre les fournisseurs/agrégateurs et les systèmes de gestion de l'énergie des clients permettant une réaction autonome à un signal DR. Alors que l'utilisation de SEP 2.0 est limitée aux appareils haut de gamme [3], le modèle plus générique IPSO Smart Objects [2], basé sur la spécification Lightweight Machine to Machine (M2M), fournit un modèle d'objet simple et flexible, adapté aux dispositifs contraints.

2.4 Considérations liées à l'interopérabilité

Le manque d'interopérabilité, l'hétérogénéité et la complexité entravent l'innovation et la création de valeur client. Alors, le défi consiste à concevoir des écosystèmes ouverts et interopérables pour le développement d'applications, l'échange de données et le partage de ressources, afin de favoriser le développement de services axés sur la création de valeur pour les clients.

Approches vers des écosystèmes interopérables

Dans cette section, nous caractérisons les approches actuelles pour la création d'écosystèmes interopérables en fonction de leur distribution des données et de l'intelligence : au niveau du *back-end*, de la passerelle et/ou de façon distribuée. Les trois possibilités sont valables et peuvent être combinées pour fournir une architecture de bout en bout.

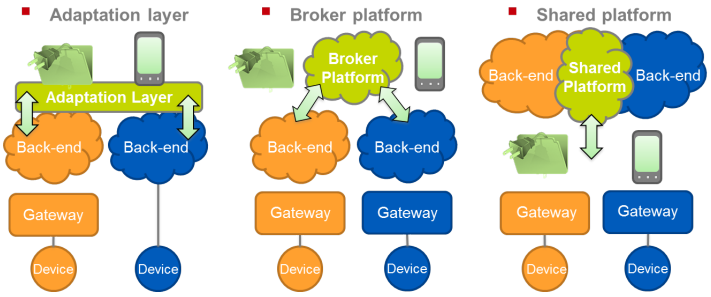
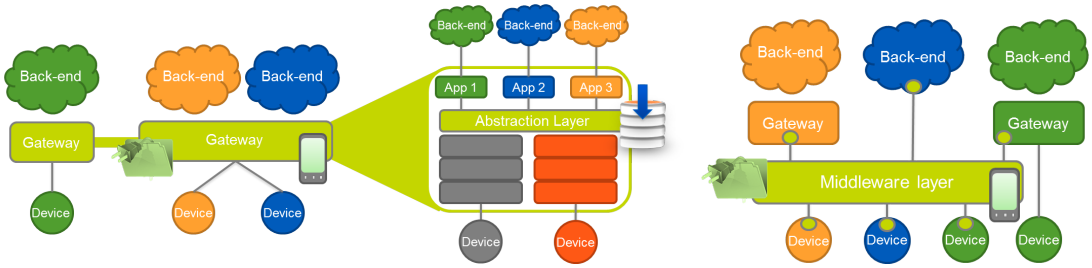


FIGURE 1 – Interopérabilité au niveau du *Back-end*.

Interopérabilité au niveau du *Back-end* - L'interopérabilité acquise au *back-end* de l'architecture repose principalement sur l'exposition des Application Programming Interface (API)s web sur un *stack* de protocoles commune (OAuth 2.0, JavaScript Object Notation (JSON), HTTP, TCP/IP). Il y a trois types d'approches vers l'interopérabilité au niveau du *back-end* (Figure 1). Le premier est basé sur une couche d'adaptation distribuée, basée sur une structure des APIs et une sémantique communes, tel que le *framework* HyperCat. Le deuxième type exploite une plateforme de courtage, en charge de la traduction entre APIs hétérogènes et des modèles de données exposés par les plateforme « client ». IFTTT, Wink et Temboo sont des exemples pertinents de ces plateforme. La troisième approche est une plateforme cloud partagée, imposant des APIs et un modèle d'objet pour avoir accès à un entrepôt de données partagées. Works With Nest, Google Fit, ThingWorks et OneM2M sont des exemples d'une telle plateforme partagée. En ce qui concerne la protection de la vie privée, la centralisation



(a) Passerelle interopérable (b) Interopérabilité distribuée

FIGURE 2 – Interopérabilité au niveau des locaux du client.

des données et leur traitement sur le cloud posent des défis quant à l'application des politiques de confidentialité, notamment en termes de contrôle de l'utilisation des données.

Passerelles interopérables - La particularité de l'interopérabilité au niveau de la passerelle est la nécessité d'une couche d'abstraction pour gérer l'hétérogénéité des protocoles de communication (Figure 2a). Basé sur un modèle de données partagées, cette couche fournit un ensemble commun d'APIs pour le découplage des applications des diverses implémentations de objets connectés, permettant de répartir la logique d'application entre le *back-end* et la passerelle. Cela réduirait les coûts d'infrastructure et pourrait améliorer la sécurité et la protection de la vie privée [4]. Les meilleurs exemples d'un tel cadre sont Apple HomeKit et HealthKit.

Interopérabilité distribuée *Peer-to-Peer* - Une couche *middleware* permet la communication de périphérique à périphérique de façon agnostique à la plateforme et au *stack* de protocoles (Figure 2b). Ainsi, tout dispositif ayant suffisamment de capacités deviendrait une passerelle interopérable pour d'autres dispositifs contraints, permettant des implémentations distribuées de la plupart des NGF. Un tel écosystème distribué nécessite une orchestration complexe des transactions entre les appareils pour faire appliquer les politiques des utilisateurs tout en évitant les conflits entre les différents services. Le principal exemple de ce type d'interopérabilité est fourni par IoTivity (Open Interconnect Consortium (OIC)).

2.5 Améliorations générales de l'architecture

Les services de la *Smart Home* sont fournis à travers des architectures en silos qui font de l'interopérabilité entre les appareils et services de différents domaines une entreprise difficile. Cette section aborde un des principaux problèmes qui entravent le développement des services IoT innovants : l'orchestration entre appareils/services de différents fabricants/domaines.

Orchestration des transactions entre contrôleurs multiservices

Après avoir passé en revue le problème d'interopérabilité dans l'IoT et les technologies existantes qui ouvrent la voie à sa solution, nous abordons maintenant le défi de l'orchestration de périphériques. Suivant la tendance à la distribution d'intelligence vers la périphérie, on peut imaginer plusieurs contrôleurs dédiés pour fournir des services sur des domaines tels que la santé, la sécurité, l'énergie, etc. Les processus de décision de ces contrôleurs poursuivent des objectifs différents mais peuvent partager d'actionneurs ou la même portée environnementale. Le manque d'orchestration entre les contrôleurs conduira à des conflits qui peuvent compromettre l'interopérabilité et augmenter la complexité des services [5].

Une approche transactive distribuée - Les problèmes liés aux transactions numériques conflictuelles sont généralement résolus en faisant confiance à une seule entité chargée de centraliser les données, de suivre l'état des objets et de gérer les transactions pour éviter les conflits. Nous envisageons la mise en place d'une telle fonction (en tant que NGF), mais de manière distribuée et transparente. Une plateforme ouverte basée sur la technologie blockchain et des contrats intelligents pourrait nativement renforcer la sécurité des transactions et résoudre les problèmes d'orchestration sans dépendre d'une entité centrale. Une telle plateforme peut permettre aux services de differents fournisseurs d'échanger des données et des ressources.

Mécanisme de transaction distribuée basée sur Blockchain - Lorsque deux parties souhaitent établir une transaction numérique sur un réseau distribué, elles doivent revendiquer la propriété des actifs numériques concernés et s'assurer que les transactions sont irréversibles, en particulier lorsque les transactions numériques comprennent des services physiques non-réversibles. Bitcoin a fourni la première solution pratique pour éviter que les transactions soient annulées en l'absence d'une entité de compensation centralisée (problème de *double-spending*), en permettant des accords distribués sur la validité des transactions, en établissant une chaîne de propriété appelée blockchain. Une blockchain rend très difficile et coûteux pour un attaquant de bifurquer la chaîne pour introduire des transactions invalides. De plus, blockchain permet d'exécuter du code sous forme de contrats intelligents de manière distribuée et extrêmement fiable, et peut donc avoir de nombreuses applications au-delà des cryptomonnaies.

Une chaîne de propriété pour éviter les conflits - Les conflits peuvent être vus comme une *double-spending* des ressources, où une ressource est un ou plusieurs objets (p. ex. : actionneurs) ou une variable environnementale (p. ex. : température) dans un certain contexte (p. ex. : période de temps). Un contrat intelligent est établi pour éviter que deux entités partagent le contrôle d'une certaine ressource en même temps, en imposant automatiquement les moyens acceptables d'échange de propriété sur le contrôle, en tant que règles d'événement-condition-action (Event-Condition-Action (ECA)). Une chaîne de blocs conserve une trace des transferts de contrôle, permettant la résolution des conflits de manière rentable, transparente et vérifiable. Le fait d'appliquer les règles ECA entièrement sur place améliorera la sécurité, la confidentialité et la disponibilité des services.

Les défis d'une blockchain résidentielle

L'un des plus grands défis consiste à garantir l'efficacité de l'algorithme de consensus et la sécurisation du réseau (par exemple : des *Sybil attacks*), qui peuvent être ébranlés par le manque d'incitations. Comme alternative à la cryptomonnaie, nous envisageons un jeton de réputation, représentant la valeur que les fabricants d'appareils fournissent en sécurisant activement le réseau, en permettant l'interopérabilité et l'accord distribué. Deux autres défis qui devraient être analysés par des travaux ultérieurs sont la possibilité de permettre des micro-transactions à une vitesse suffisamment rapide pour fournir des services impliquant l'interaction des utilisateurs, et d'évaluer/minimiser l'impact des bifurcations (inconsistance) temporaires dans la blockchain sur l'interaction entre contrôleurs et actionneurs.

3 Gestion du réseau de distribution

3.1 Objectifs d'un *Smart Grid* local

L'objectif principal d'un réseau de distribution intelligent est de renforcer l'efficacité, la fiabilité et la qualité de l'approvisionnement en énergie, en jouant en particulier sur la flexibilité de la demande. Le *smart grid* permet :

- L'équilibrage énergétique local, en coordonnant des ressources énergétiques réparties au niveau du réseau de distribution (quartier, poste source). Cela vise à réduire les transits et les pertes et, par conséquent, à augmenter la capacité d'hébergement de la production locale.
- Le pilotage des flexibilités, directement ou en passant par un agrégateur, afin de contrôler la tension et les transits.
- Une collaboration avec les acteurs des marchés locaux et nationaux (producteurs, transporteur, fournisseurs et agrégateurs) avec l'objectif d'une optimisation de l'équilibre offre-demande local et/ou global.
- Des gains sur la facture énergétique des prosumers avec des impacts limités sur leur confort et leur vie privée.

3.2 Exigences pour un smart grid

Les exigences pour une architecture de smart grid sont les suivantes :
- Fiabilité/Tolérance aux pannes - L'architecture doit fonctionner de manière fiable en cas d'erreurs de communication.
- Flexibilité et extensibilité. Elle doit avoir des capacités *Plug and Play* permettant de gérer l'ajout et la suppression des ressources distribuées.
- Évolutivité - L'architecture doit s'adapter à l'hétérogénéité des ressources et des acteurs impliqués.
- Faible coût de mise en œuvre et de maintenance.
- Évolution indépendante des stratégies de contrôle, à différents niveaux (logement, réseau de distribution, niveau système), pour faire face à la progression rapide des technologies et des mécanismes de contrôle.
- Efficience et équité. Les mécanismes de gestion de l'énergie devront maximiser la valeur tirée des ressources flexibles et assurer une répartition équitable entre les acteurs.

3.3 Approches actuelles pour la gestion des ressources énergétiques distribuées

Les deux principales approches pour gérer les ressources énergétiques distribuées (moyens de production, charges modulables, stockage électrique) sont les Microgrids et les Virtual Power Plants (VPP). Les microgrids (micro-réseaux) se définissent comme une partie de réseau disposant de moyen de production d'énergie, avec un point de connexion unique au réseau principal. Cela permet au micro-réseau d'être, à certaines périodes, séparé du réseau principal (ilotage) pour fonctionner en autonomie complète. En revanche le microgrid nécessite un opérateur unique responsable des échanges d'énergie avec le réseau principal lors des phases de connexion (Figure 3). Les microgrids sont par exemple adaptés à des campus universitaires ou à des petites communautés. Les microgrids impactent les règles de marché actuelles et obligent à repenser les rôles des acteurs du modèle de réseau global standard (distributeur, agrégateurs, responsables de l'équilibre...).

De leur côté, les VPP s'adressent au marché national en substituant à des moyens de production centralisés, l'agrégation de petites productions (ou d'effacements de consommation) répartis sur les réseaux de distribution. Les VPP sont mises en œuvre par le biais de contrats entre les agrégateurs et les propriétaires des ressources énergétiques réparties (producteurs ou consommateurs) raccordées

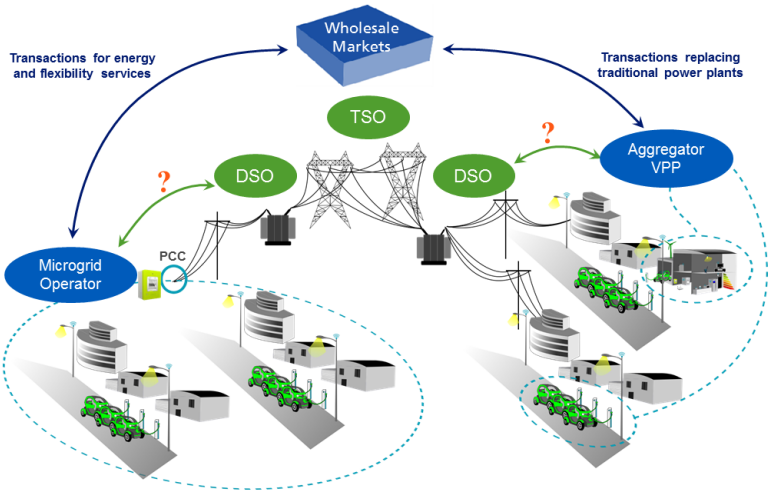


FIGURE 3 – Approches Microgrid et VPP

au réseau de distribution. Les VPP agrègent des flexibilités de production ou de consommation pour les besoins des marchés nationaux mais elles nécessitent une coordination avec les distributeurs sous peine d'introduire des contraintes sur les réseaux locaux.

3.4 Nouvelle architecture pour la gestion de la production raccordée au réseau local

Réseaux virtuels de distribution

Le réseau de distribution d'électricité n'a pas été conçu pour faire face à une pénétration massive de véhicules électriques, ni pour faire face au déploiement croissant des sources d'énergie renouvelable distribuées. Les gestionnaires de réseau de distribution devront de plus en plus utiliser la flexibilité des ressources énergétiques distribuées (charges modulables, production et stockage) pour maintenir la qualité de l'approvisionnement. Les approches actuelles de gestion de ressources énergétiques réparties se concentrent sur l'agrégation des flexibilités de production et de consommation pour participer aux marchés nationaux (marché de capacité, mécanisme d'ajustement), sans chercher une coordination des acteurs au niveau du réseau local. Nous proposons la création de réseaux de distribution virtuels VDG sur une infrastructure physique commune, pour faire face à l'hétérogénéité des ressources et des acteurs, et à la complexité croissante de la gestion des réseaux de distribution et des problèmes d'allocation des ressources. En se concentrant sur les réseaux virtuels de distribution basse tension, nous proposons une architecture hiérarchique basée sur des agents de gestion de la demande participant à un marché local : les habitants échangent l'énergie excédentaire de leur logement avec leurs voisins et apportent les flexibilités utiles au fonctionnement du réseau local, avec le concours d'agrégateurs, et de fournisseurs d'énergie. L'approche est compatible avec les microgrids et les VPP, car elle ne cible pas la participation au marché national, mais prévoit que les microgrids et les VPP négocient l'accès aux flexibilités via un mécanisme d'allocation local en interaction avec les mécanismes nationaux. Les flexibilités concernées sont apportées par différents acteurs (clients résidentiels, commerciaux et industriels, bornes de recharge de véhicules électriques, fournisseurs de services énergétiques, agrégateurs, etc.) dont les objectifs ne sont pas nécessairement alignés sur les besoins du réseau de distribution. Chaque réseau virtuel de distribution est constitué de différents blocs architecturaux avec des algorithmes de gestion spécifiques. Nous pouvons par exemple envisager un réseau virtuel de distribution pour la gestion de l'énergie produite et consommée au niveau

d'un quartier et un autre pour la gestion de la recharge des véhicules électriques sur le réseau de distribution (Figure 4). Le rôle du gestionnaire de réseau est dans ce cas analogue à celui d'un hyperviseur sur un environnement Cloud, chargé de maintenir un comportement global cohérent entre la gestion de l'infrastructure et la gestion de l'énergie. Les gestionnaires des réseaux surveillent les ressources physiques et, pour limiter les contraintes, peuvent fixer des consignes à chaque processus d'allocation de ressources sur les réseaux virtuels , ou transmettre des signaux adéquats aux acteurs pour les inciter à adapter leur comportement. Certains réseaux virtuels de distribution pourront être prioritaires sur d'autres, soit pour limiter les transits, soit pour offrir des qualités de services d'accès au réseau différenciées.

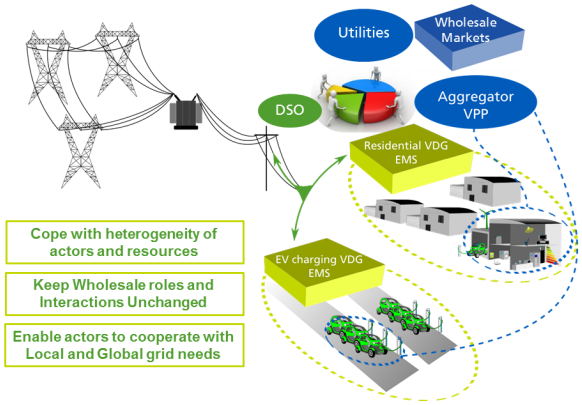


FIGURE 4 – Approche *Virtual Distribution Grids*

Un système de gestion de l'énergie doit fournir un contrôle transparent des ressources énergétiques permettant leur allocation pour différents usages potentiellement concurrents :

- équilibrage production/consommation au sein d'un réseau virtuel,
- participation aux mécanismes de marchés nationaux,
- fourniture de services au distributeur pour la gestion de la tension et du transit sur réseau local.

Les utilisateurs de ces ressources peuvent être en compétition lorsque la flexibilité a la plus forte valeur commerciale, notamment lorsque le réseau est le plus contraint.

L'étude s'est focalisée sur le système de gestion d'un réseau virtuel de distribution indépendamment du rôle que le distributeur pourrait jouer dans leur gestion. Elle cible la gestion des ressources des prosumers à l'échelle d'un quartier. En particulier, nous nous sommes intéressés à l'autoconsommation collective de la production d'énergie solaire, en tirant parti des technologies IoT pour communiquer, surveiller et contrôler les flexibilités issues de smart homes. L'architecture de gestion des réseaux virtuels de distribution a été conçue avec une attention particulière vis-à-vis de l'interopérabilité des solutions, de la répartition de l'intelligence, de la sécurité et de la confidentialité des données, ces aspects jouant un rôle majeur sur la viabilité d'une architecture IoT.

Architecture du système de gestion énergétique local

Les approches centralisées de gestion de l'énergie sur les réseaux de distribution reposent sur une entité unique chargé de collecter des données et de calculer les points de consignes optimales de chaque ressource contrôlée. Une gestion centralisée nécessite des ressources de communication

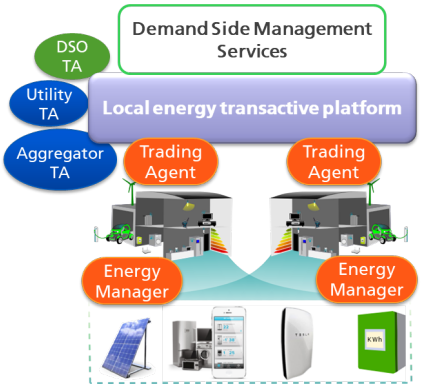


FIGURE 5 – Architecture hiérarchique pour la gestion du réseau électrique.

et des capacités de calcul étendues avec une faible adaptabilité. En outre, un système centralisé ne garantit pas l'accès à toute l'information, certains participants pouvant la bloquer ou la déformer en fonction de leurs propres objectifs (choix des clients en matière de confort ou d'autoconsommation, par exemple). De plus, certaines informations telles la présence des habitants peuvent ne pas être partagées pour des raisons de confidentialité.

D'un autre côté, des approches entièrement décentralisées dont les décisions se basent sur des informations locales, sans coordination, peuvent conduire à une oscillation de la réponse globale. En particulier, il existe déjà de nombreuses technologies permettant réduire la facture énergétique ou de maximiser l'autoconsommation individuelle des bâtiments disposant de moyens de production PhotoVoltaic (PV) et/ou de stockage électrique. Ces systèmes ne prennent pas en compte des besoins d'équilibrage local ou global de la production et de la consommation. Par conséquent, de tels systèmes autonomes peuvent créer ou accentuer des déséquilibres récurrents sur le réseau. Pour un réseau virtuel de distribution, même peu étendu, le nombre de ressources distribuées peut être conséquent et nécessiter des communications haut-débit et de lourds calculs des points de consigne de l'ensemble des ressources. Une approche hiérarchique est susceptible de réduire considérablement les exigences pour la collecte et le traitement des données. Aussi, nous proposons une hiérarchie de stratégies de contrôle basée sur des optimisations individuelles de la facture énergétique de chaque logement, associée à une allocation des ressources au niveau du réseau de distribution (Figure 5).

Contrôle au niveau du réseau de distribution

L'optimisation de la gestion des ressources énergétiques réparties, nécessite une coordination des acteurs du réseau de distribution. Nous proposons la mise en œuvre de mécanismes de marché permettant la coordination et la collaboration de « Trading Agents » situés notamment au niveau de chaque logement, grâce à une plateforme de gestion des transactions énergétiques (Figure 5). Les marchés paraissent en effet être un mécanisme approprié pour contrôler des ressources réparties issues d'entités autonomes. Les agents négocieront les ressources énergétiques entre eux afin de satisfaire des objectifs économiques (réduction du coût énergétique de chaque logement) tout en intégrant les contraintes d'exploitation du réseau local. Les distributeurs implémenteront des agents pour chaque réseau virtuel de distribution, chargés de maintenir la qualité et la sécurité de l'alimentation, en fonction de contraintes prévues sur le réseau. Les Responsables d'Équilibre et les autres acteurs participant aux marchés nationaux auront des agents sur chaque réseau virtuel de distribution leur fournissant des informations sur le comportement énergétique des clients de leur portefeuille, et leur permettant d'optimiser leurs offres sur les marchés nationaux.

Bien que les modèles d'affaires sortent du cadre de l'étude, nous considérons que les règlementa-

tions actuelles de la plupart des pays européens ne sont pas favorables à l'exploitation de la flexibilité des ressources réparties, mais nous supposons qu'elles évolueront dans le bon sens.

3.5 Mise en œuvre de la nouvelle architecture

Plateforme transactionnelle

La création d'applications permettant des transactions distribuées sur une infrastructure partagée par des acteurs en concurrence est récemment devenue possible grâce à la technologie blockchain. Le réseau est composé de nœuds de validation, par exemple mis en œuvre par des fournisseurs de services, chargés de transmettre et de traiter les blocs de transactions, et de valider l'ajout de nouveaux blocs sur un registre partagé. Ce registre partagé fonctionne comme une machine d'état répliquée, dans laquelle un nouveau bloc représente un accord entre les participants sur le nouvel état du registre. Le registre peut héberger du code sous la forme d'un *smart contract*, qui est exécuté chaque fois qu'une transaction lui est adressée. Ce comportement est répliqué sur les nœuds de validation et permet au système de traiter les transactions de manière sécurisée et fiable, même en présence de nœuds malveillants. Nous utilisons la technologie blockchain pour construire une chaîne historisant les ressources énergétiques (volumes d'énergie/flexibilité) échangées et les rémunérations associées. Les parties impliquées dans une transaction reçoivent également une récompense, lorsque des flux d'électricité limitent les contraintes sur le réseau. Ces récompenses sont faites à travers un jeton que nous appelons eCoin, représentant un certificat d'énergie verte échangé localement, qui peut avoir de nombreuses applications liées à l'efficacité énergétique ou à la réduction des émissions de CO2. Nous avons utilisé des réseaux de *smart contracts* pour implémenter chaque aspect du marché (Figure 6), dont le registre des énergies échangées, les offres correspondantes sur un mécanisme d'enchères, et l'attribution des eCoins. La plateforme Monax a été utilisée pour créer le réseau de nœuds de validation, qui permettent d'obtenir un accord distribué grâce à l'algorithme Tendermint Byzantine Fault Tolerance. Monax fournit également les outils pour déployer des smart contracts et les bibliothèques utilisées par les *trading agents* pour interagir avec le réseau de validateurs.

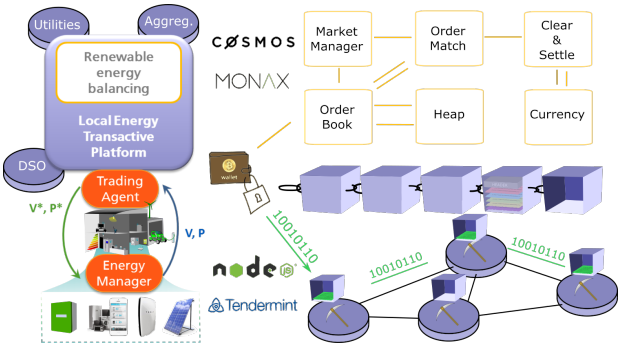


FIGURE 6 – Plateforme Blockchain-based transactive platform and market implementation.

En complément des marchés visant l'équilibre production/consommation local qui seront présentés dans la section suivante, la blockchain permettra à tout agrégateur ou fournisseur d'offrir des services complémentaires de gestion de demande. Par exemple, les *smart contracts* permettront aux clients de proposer des flexibilités à plusieurs agrégateurs concurrents, sans contractualisation préalable. La plateforme est conçue pour permettre l'exécution fiable de transactions transparentes et auditables entre les acteurs. De plus, l'historique des transactions partagées pourrait être utilisé comme une source de réputation des différents acteurs (fournisseurs, agrégateurs, prosumers).

4 Marché locale d'énergie

Dans la section précédente nous avons présenté une architecture qui permet aux logements d'exploiter la flexibilité provenant des objets qui consomment, stockent ou produisent de l'énergie, et d'échanger de manière autonome des blocs d'énergie et des services de flexibilité avec des logements voisins, et des acteurs du marché (fournisseurs/acheteurs d'énergie, agrégateurs). Dans la présente section nous proposons, en tant qu'application, un marché local afin d'équilibrer les productions d'énergie solaire et les consommations à l'échelle d'un quartier. Nous proposons un mécanisme d'enchères, en charge de faire correspondre de maniéré efficace les offres d'achat et de vente d'énergie, et un prix d'acheminement dynamique que, ensemble, permettent d'inciter les logements à contrôler localement leurs ressources flexibles d'une façon que rapporte des bénéfices pour eux et pour l'opérateur du réseau de distribution. D'une part, les logements échangent de manière autonome des blocs d'énergie avec leurs voisins afin d'optimiser leur facture énergétique, et d'autre part le gestionnaire de réseau de distribution favorise la synchronisation des consommations avec la production locale intermittente.

4.1 *Related Work*

Les travaux antérieurs sur les échanges d'énergie entre maisons ont principalement porté sur des enchères doubles continues [3] [7,8], qui sont difficiles à implémenter dans une plateforme distribuée, alors que les marchés d'appels dans lesquels les ordres sont assortis périodiquement [9, 10], sont mieux adaptés et peuvent aussi être plus efficaces [11]. La plupart des articles prenant en compte l'impact de tels marchés sur le réseau de distribution repose sur *locational marginal pricing* [12,13] ou sur *message passing* [14], qui nécessitent des connaissances spécifiques sur la topologie du réseau et pénalisent les ménages selon leur localisation. Il existe une tendance récente vers des marchés locaux pour l'échange d'énergie entre maisons sur des plateformes distribuées. Les approches actuellement basées sur la blockchain ne sont pas axées sur l'équilibre local des énergies renouvelables ou ne tiennent pas compte des besoins existants du réseau de distribution[4] [15].

4.2 Description du système

Le réseau de distribution à basse tension étudié comprend un transformateur Moyenne Tension / Basse Tension (MT/BT) et un ou plusieurs départs auxquels les maisons sont connectés, dans un contexte de déploiement important de PV et de batteries stationnaires rechargeables. Nous considérons les maisons avec des differents types de ressources énergétiques distribuées [5] (DER), incluant des compteurs intelligents. Les batteries représentent l'unique source de flexibilité, car dans cette section nous considérons la demande inélastique, de sorte qu'il n'y a pas d'impact sur le confort et qu'une interaction minimale de l'utilisateur est requise. Nous supposons également que les flux provenant de la PV et de/vers la batterie peuvent être contrôlés au moyen d'onduleurs intelligents. Cela permet aux ménages de contrôler la destination de l'excès d'énergie renouvelable ainsi que la source d'énergie qui répond aux demandes de charge.

Les ménages interagissent entre eux et avec le DSO, les fournisseurs d'électricité et de services à travers une plateforme transactionnelle locale pour coordonner l'accès au Distributed Energy Resources (DER). Ces acteurs sont représentés par des agents qui transigent de manière autonome des ressources énergétiques entre eux afin d'atteindre leurs objectifs économiques, tout en collaborant avec les besoins du réseau local et global. Les ménages comptent sur une fonction de gestion de l'énergie (Home Energy Management System (EMS) (HEMS)) pour optimiser l'allocation de DER en fonction des politiques du prosumer et des incitations économiques, et un agent de trading avec la capacité d'échanger les ressources sur la plateforme distribuée.

[3] Les offres d'achat ou de vente sont appariées dès leur arrivée dans l'ordre d'arrivée.

[4] http://brooklynmicrogrid.com/, https://powerledger.io/, http://solarcoin.org/

[5] Charges flexibles, ressources de production et de stockage contrôlables

Marché local pour l'équilibrage de l'énergie renouvelable

Ce travail se concentre sur les marchés d'équilibrage des énergies renouvelables au niveau du quartier, où les ménages peuvent échanger leurs excédents/manque d'énergie. Sur la base de l'écart prévu entre la consommation et la production, le HEMS définit l'énergie à échanger afin de minimiser la facture d'électricité. Ensuite, les offres des agents de trading des ménages sont traitées par un algorithme d'enchères qui définit les quantités acceptées à échanger et les prix correspondants.

En termes d'échelles de temps, nous nous concentrons sur les échanges intra-journaliers de blocs d'énergie correspondant à des périodes de 10 minutes[6]. Chaque période de marché atteindra la finalité au moins une heure avant le temps dans lequel les ressources sont allouées. Cela donne aux acteurs du marché le temps d'adapter leurs offres sur le marché de gros, car l'énergie non équilibrée localement est fournie/absorbée par les fournisseurs d'électricité.

Afin d'évaluer le potentiel des marchés locales pour augmenter la capacité du réseau d'héberger des sources d'énergie renouvelable (Renewable Energy Sources (RES)), nous considérons les flux agrégés et maximaux à travers le transformateur, le Peak to Average Ratio (PAR), et les pertes respectives ; tandis que pour les lignes, nous analysons également les pertes ainsi que les déviations de tension et le déséquilibre du réseau.

Prix et autoconsommation

Dans un contexte de déploiement massif de production solaire, nous supposons que les prix d'achat de l'électricité produite par des moyens centralisés sont plus élevés que le coût de l'énergie solaire (coût complet intégrant l'investissement actualisé et les coûts de maintenance). Nous considérons que le tarif de rachat (Feed In Tariff (FIT)) est devenu inférieur au coût de l'énergie solaire, ce qui encourage des transactions sur un marché l'échange d'énergie entre les logements, et contribue à équilibrer localement la consommation et la production d'énergie renouvelable.

Nous prenons pour hypothèse que les maisons privilégient l'autoconsommation de l'énergie produite par leurs panneaux PV et qu'elles ne vendent que leurs excédents de production. Les injections d'énergie sur le réseau peuvent toutefois être encouragés (p. ex. : par des incitations financières) aux périodes où elles apportent de la valeur pour la gestion du système électrique (valeur pour le réseau local et valeur pour l'optimisation de équilibre global offre-demande).

En cas d'excédent de production, les logements peuvent utiliser le surplus d'énergie pour :

- charger leur batterie,
- injecter de l'énergie sur le réseau pour la vendre au Tarif de Rachat
- vendre à un prix négocié sur le marché local des énergies renouvelables.

En cas de consommation supérieure à la production de la maison, les logements peuvent compléter leur production solaire en :

- déchargeant leur batterie,
- soutirant de l'énergie sur le réseau au tarif contractualisé avec un fournisseur d'énergie,
- achetant de l'énergie sur le marché local des productions renouvelables.

Ainsi, seule l'énergie contribuant à l'équilibre local serait récompensée et motiverait en même temps les agents à respecter les engagements de fourniture/achat sur le marché local. Cette approche profite non seulement à ceux qui investissent dans la production photovoltaïque mais aussi aux clients acceptant de moduler leur consommation, et qui apportent ainsi la flexibilité nécessaire à l'accueil des énergies renouvelables. Néanmoins, les incitations induites par le fonctionnement du marché ne

[6] portée temporelle en raison des contraintes imposées par la réglementation sur les déviations de tension [16, 17].

peuvent pas résoudre toutes les contraintes d'exploitation du réseau, et des incitations dynamiques doivent être superposées par le distributeur pour inciter, par exemple, les logements à recharger leurs batteries en cas d'excédent d'énergie au niveau du quartier (vu du poste de distribution).

4.3 Métriques pour évaluer l'impact du marché

Dans cette section, nous décrivons les métriques de qualité pris en compte pour l'évaluation du marché proposé. Nous considérons des périodes de 24 heures, fendues dans des intervalles de temps de 10 minutes, $t \in \mathcal{T} = 1, ..., T$, où $T = 144$ est le montant total des intervalles de temps. Soit $P_{in,t}$ la puissance qui traverse le transformateur de MV vers LV à un intervalle de temps t, exprimé comme $P_{in,t} = \sum_{ph} \max(P^P_{ph,t}, 0)$, où $P^P_{ph,t}$ est la puissance sur les enroulements primaires pour la phase ph, et $P_{out,t} = \sum_{ph} \max(-P^S_{ph,t}, 0)$ le flux de LV vers MV, où $P^S_{ph,t}$ est le pouvoir sur les enroulements secondaires. La puissance totale traversant le transformateur est donnée par $P_{abs,t} = P_{in,t} + P_{out,t}$. Compte tenu des flux à travers le transformateur, nous définissons les pertes correspondantes comme suit :

$$Tr_{loss} = \sum_t (P_{abs,t}(C_L + C_C)) \tag{1a}$$

$$L_{loss} = \sum_{l,ph,t} R_{l,ph} I^2_{l,ph,t} \tag{1b}$$

où C_L et C_C sont les coefficients représentant les pertes par inductance de fuite et les pertes de cuivre dues aux courants circulant dans les enroulements du transformateur, respectivement. Sur les pertes de ligne, $R_{l,ph}$ est la résistance de la phase ph de la section l de la ligne, et $I_{l,ph,t}$ le courant correspondant.

En ce qui concerne le pic de puissance à travers le transformateur :

$$P_{max} = \max(P_{abs,t}) \tag{2a}$$

$$PAR = T \frac{P_{max}}{\sum_t P_{abs,t}} \tag{2b}$$

La capacité d'hébergement des RES est également affectée par des problèmes de tension tels que des déviations de tension par rapport à sa valeur nominale ainsi que le déséquilibre du réseau. La valeur nominale V_U et l'écart de tension V^{ph}_{delta} pour chaque phase ph sont définis comme suit, avec V^{ph}_{L2N} étant la tension de ligne à neutre :

$$V_U = \frac{410}{\sqrt{3}} \tag{3a}$$

$$V^{ph}_{delta} = 100 \frac{|V^{ph}_{L2N}| - V_U}{V_U} \tag{3b}$$

$$VUF = 100 \frac{|V_2|}{|V_1|} \tag{3c}$$

Où V_1 et V_2 sont les tensions positive et négative selon la méthode des composants symétriques pour les systèmes d'alimentation non équilibrés et VUF est le facteur de déséquilibre de la tension.

Mécanisme de marché

Le mécanisme de marché consiste à déterminer les quantités et prix négociés par chaque participant, en faisant correspondre leurs ordres d'achat et de vente. Les échanges de blocs d'énergie entre les agents sont effectués à travers un mécanisme d'enchères Multi-unit Double Auction (MDA) [11], où les agents soumettent une offre (ou une demande), qui est le prix maximum (ou minimum), que l'agent est prêt à payer pour acheter (ou accepter de vendre) les blocs d'énergie sur certains créneaux

horaires. Nous proposons un mécanisme MDA en temps discret, basé sur un algorithme qui comporte des caractéristiques intéressantes [18] :

- *Strategy-proof* - La stratégie optimale de chaque agent révèle des informations fiables indépendamment des actions d'autres agents.
- *Weakly budget-balanced* - Tous les paiements entre les acheteurs et les vendeurs laissent un montant résiduel utilisé pour récompenser les nœuds qui traitent les transactions.
- *Individually rational* - Le marché encourage la participation en assurant des profits.
- *Asymptotically efficient* - Le marché devient plus efficace lorsque le nombre de participants augmente.

Le marché fonctionne avec un cycle quotidien et un pas de 10 minutes, durant lequel les offres sont considérées statiques. A chaque pas, chaque acteur soumet une offre d'achat ou de vente. Le mécanisme génère d'abord la courbe offre/demande qui trie les offres et les demandes respectivement dans l'ordre décroissant et croissant de leur prix de réservation. Les acheteurs et vendeurs sont identifiés au point où la demande et l'offre se rencontrent.

Incitations de prix

En plus de la récompense FIT supplémentaire proposée dans la Section 1, une incitation dynamique doit être envisagée pour synchroniser la charge de la batterie avec l'énergie renouvelable disponible localement. Nous proposons la forme de l'incitation à être un rabais sur les frais de distribution/transport pour ceux qui achètent de l'électricité sur le marché local, car chaque Wh échangés par le marché est supposé de ne pas traverser le transformateur. Nous proposons que la valeur soit proportionnelle à la prévision journalière de la production moyenne d'énergie renouvelable d'une maison sur le quartier. Soit r^m la ristourne maximale considérée, $p^u = p_1^u, ..., p_T^u$ comme prix du fournisseur pour la journée, et $\hat{g}^n = \hat{g}_1^n, ..., \hat{g}_T^n$ soit la prévision pour la production renouvelable moyenne, où les valeurs sont normalisées pour que $\hat{g}_t^n \leq 1 \ \forall t$. Alors le prix minimum de réservation pour chaque maison au temps t serait $p_t^r = p_t^u - \hat{g}_t^n r^m$ plutôt que p_t^u, ce qui signifie que les maisons peuvent potentiellement gagner plus en faisant des offres pour charger leurs batteries quand il y a plus d'énergie renouvelable disponible.

4.4 Définition du problème des ménages

Nous considérons une architecture hiérarchique où le contrôle sur le niveau de la grille de distribution, basé sur les mécanismes de marché comme expliqué ci-dessus, peut être conçu indépendamment des mécanismes de contrôle à l'intérieur des ménages, ce qui constitue un avantage par rapport aux modèles couplés. Pour illustrer la faisabilité de notre approche, un modèle simple des problèmes qui doivent être résolus par le HEMS est décrit. Aux fins de cet article, nous considérons un scénario déterministe dans lequel les courbes de consommation et de production sont connues à l'avance. Cette hypothèse simplificatrice repose sur la capacité des batteries à absorber les erreurs de prévision, en particulier si les prévisions étaient biaisées en moyenne nulle, et sur la possibilité d'établir des mécanismes de marché similaires plus proches du temps réel.

Déterminer la quantité à offrir

Soit $h \in \mathcal{H} = \{0, ..., 23\}$ la prochaine heure pour laquelle le marché local des énergies renouvelables acceptera les offres. Le HEMS doit trouver les quantités d'offre optimales $\hat{v}^o_{t_0+1}, ..., \hat{v}^o_{t_0+6}$, où $t_0 = 6h$ est l'intervalle de temps de l'heure h pour 6 *time slots* par heure. Les unités d'énergie à proposer sur le marché dépendent de l'utilisation optimale de la batterie. La quantité d'énergie stockée sur la batterie à la fin de l'intervalle de temps t est représentée par e_t et son évolution dans le temps

est donnée par $e_t = e_{t-1} - s_t$, où s_t représente la quantité d'énergie chargée ou déchargée de/vers la batterie pendant l'intervalle de temps t. Nous demandons aux batteries de retrouver l'état de charge initial à la fin de la période $e_T = e_0$, afin que chaque étude soit indépendante et ne dépasse pas non plus un cycle complet de charge/décharge de 80 % profondeur de décharge par jour, pour prolonger la vie de la batterie.

Pour satisfaire ces contraintes de batterie, le HEMS doit optimiser sur une fenêtre roulante formée par des intervalles de temps $t \in \mathcal{T}_h = \{t_0+1, .., 144\}$, avec $\tau_h = |\mathcal{T}_h|$. Chaque ménage a une prévision de consommation ℓ_{ht} et de production g_{ht} pour le reste de la journée, à partir de laquelle il détermine l'écart $d_{ht} = \ell_{ht} - g_{ht}$ qui doit être obtenu en chargeant/déchargeant la batterie ou en achetant/vendant sur le marché local. Les ménages sont incités à offrir sur le marché local toute l'énergie qui n'est pas échangée avec la batterie, puisqu'ils paient au plus leur prix limite d'offre p^b lorsqu'ils achètent et reçoivent au moins leur prix limite demandé p^a lors de la vente.

Ensuite, chaque ménage examinera le reste de la journée et déterminera la meilleure façon d'utiliser la batterie afin de minimiser la facture d'électricité, en fonction de leurs prix limites et en supposant que toutes les offres seront acceptées. Pour chaque heure h le HEMS résoudra le programme linéaire suivant :

$$\arg\min_{x_h} a_h^T x_h \qquad a_h \in \Re^{3\tau_h}, x_h \in \Re^{3\tau_h} \tag{4a}$$

s.t.

$$x_{1,ht} + x_{2,ht} + x_{3,ht} = d_{ht} \qquad \forall\ t \in \mathcal{T}_h \tag{4b}$$

$$-e_{h0} \leq -\sum_{t_0+1}^{t} x_{3,ht} \leq E - e_{h0} \qquad \forall\ t \in \mathcal{T}_h \tag{4c}$$

$$-C^u \leq x_{1,ht} \leq 0 \qquad \forall\ t \in \mathcal{T}_h \tag{4d}$$

$$0 \leq x_{2,ht} \leq C^u \qquad \forall\ t \in \mathcal{T}_h \tag{4e}$$

$$|x_{3,ht}| \leq C^s \qquad \forall\ t \in \mathcal{T}_h \tag{4f}$$

où e_{h0} est l'énergie accumulée sur la batterie jusqu'à l'heure h, C^u et C^s sont la puissance maximale qui peut être échangée sur un intervalle de temps de 10 minutes avec la grille et le batterie respectivement. Variables $x_h = (x_{1,ht}^T, x_{2,ht}^T, x_{3,ht}^T)$ et coefficients déterministes $a_h = (a_{1,ht}^T, a_{2,ht}^T, a_{3,ht}^T)$ sont les suivants :

$$x_{1,t} : \hat{v}_{ht}^a \quad \text{Énergie à vendre au marché} \tag{5a}$$

$$a_{1,t} = \begin{cases} p^a, & \text{if } g_{ht} > \ell_{ht}, \\ 0, & \text{else}, \end{cases}$$

$$\begin{aligned} &x_{2,t} : \hat{v}_{ht}^b \quad \text{Énergie à acheter du marché} \\ &a_{2,t} = p^b \end{aligned} \tag{5b}$$

$$\begin{aligned} &x_{3,t} : s_{ht} \quad \text{Utilisation de la batterie} \\ &a_{3,t} = 0 \end{aligned} \tag{5c}$$

Avec la solution on obtient le vecteur d'offres $\hat{v}_h^o = \hat{v}_h^a + \hat{v}_h^b$ à partir desquelles seules les 6 premières valeurs correspondant à l'heure suivante seront envoyées au *trading agent*.

Déterminer les flux finaux

Une fois que les résultats du marché pour chaque intervalle de temps de l'heure suivante h sont obtenus par le *trading agent*, le HEMS doit ré-exécuter le problème d'optimisation afin d'obtenir le

point de consigne souhaité pour la batterie, ainsi que les flux à échanger avec le fournisseur. La structure du problème d'optimisation est la même, sauf que les quantités finalement échangées avec les voisins $v_h^o = v_h^a + v_h^b$ sont des données d'entrée et modifient l'écart à satisfaire $d_{ht} = \ell_{ht} - g_{ht} - v_{ht}^o$, et les variables et les paramètres d'optimisation sont les suivants :

$$x_{1,t} : g^{FIT} \quad \text{Énergie à vendre au fournisseur} \tag{6a}$$
$$a_{1,t} = \begin{cases} FIT, & \text{if } g_{ht} > \ell_{ht}, \\ 0, & \text{else,} \end{cases}$$

$$\begin{aligned} x_{2,t} &: \ell^u \quad \text{Energie à acheter au fournisseur } u \\ a_{2,t} &= p^u \quad \text{Prix proposé par le fournisseur } u \end{aligned} \tag{6b}$$

$$\begin{aligned} x_{3,t} &: s_{ht} \quad \text{Utilisation de la batterie} \\ a_{3,t} &= 0 \end{aligned} \tag{6c}$$

4.5 Simulations et résultats

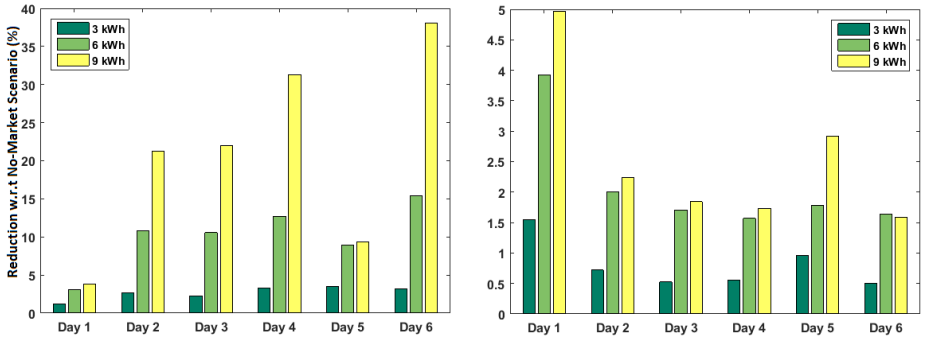
Outils de simulation, procédure et hypothèses

Nous avons évalué l'impact des marchés locaux des énergies renouvelables sur l'optimisation du réseau de distribution. Les résultats sont issus d'analyses de *load flow*, réalisées à partir de plateforme de simulation de réseau (DisNetSimPl) développée par EDF R&D. Nous avons établi, à titre illustratif, un modèle de réseau d'électricité composé d'un transformateur 20kV/400V d'une puissance nominale de 160 kVA, et de 2 départs en aluminium de 240 mm2 suivant des recommandations générales pour la conception des réseaux de distribution français. Les données de consommation au pas 10 minutes ont été générées à partir du simulateur multi-agents de comportement humain SMACH développée par EDF R&D. Les courbes de charge correspondent à 6 jours d'hiver de consommation de 33 logements de profils diversifiés (8 consommateurs, 8 prosumers avec batteries de capacité 3, 6 et 9 kWh et 17 avec des panneaux PV). Après chaque interaction avec le marché, les flux d'échange d'énergie avec la batterie et le réseau sont calculés. Les courbes de charge des échanges de chaque maison avec le réseau alimentent le simulateur DisNetSimPl pour déterminer l'impact sur le réseau de distribution. Les prix de réserve de l'énergie sur le marché des maisons ont été générés aléatoirement à partir d'une distribution uniforme avec des valeurs allant de 0 à 30% de bonus par rapport aux prix du fournisseur (sur la base d'un double tarif Heure Pleine/Heures Creuses correspondant à des prix de 15 c€/kWh de 0h à 16 h et 30 c€/kWh de 17 h à 23 h).

Résultats

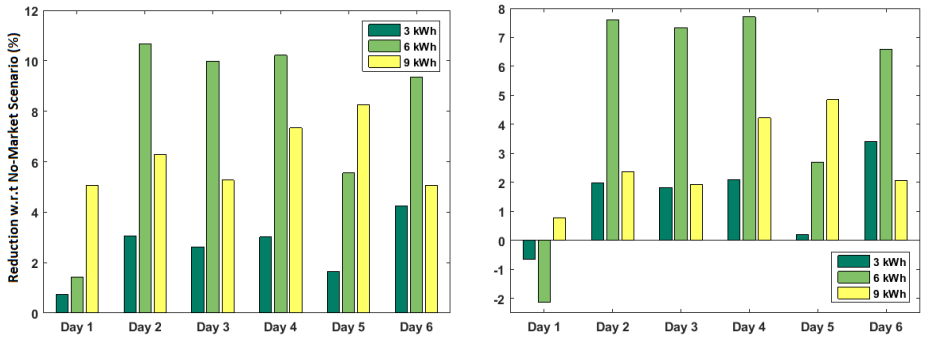
Cette synthèse se limite à présenter les résultats principaux, c'est-à-dire l'amélioration de l'équilibre production/consommation du quartier (taux d'amélioration par rapport au scénario de référence sans marché local) et la réduction de la puissance maximale vue par le transformateur. Les résultats sont affichés pendant 6 jours et pour plusieurs tailles de batteries. La Figure 7a montre qu'un marché permettant l'échange d'énergie entre les logements couplé à des incitations appropriées permet de réduire considérablement le refoulement de production d'énergie renouvelable vers le niveau HTA (meilleur équilibrage production/consommation local). On constate également une réduction conséquente de l'énergie soutirée au réseau HTA (Figure 7b), néanmoins proportionnellement plus faible que celle injectée.

L'amélioration est proportionnelle à la taille de la batterie, en cohérence avec l'augmentation de la flexibilité des logements, avec un impact moindre aux jours 1 et 5 en raison d'une demande agrégée inférieure aux heures de pointe. En revanche, l'accroissement de la taille des batteries limite les excédents de production PV des maisons et réduit par conséquent les offres de vente sur le marché.



(a) Énergie refoulée vers HTA (b) Énergie soutirée

FIGURE 7 – Réduction du flux à travers le transformateur



(a) Puissance maximale supporté par le transformateur (b) Puissance moyenne supporté par le transformateur

FIGURE 8 – Évaluation de la congestion du réseau.

La réduction du transit dans le transformateur entraîne une réduction des pertes de transformation de 4% avec les batteries résidentielles de 6 et 9 kWh. Les pertes de ligne totales sont également réduites.

Par rapport à la puissance maximale supporté par le transformateur, la Figure 8a montre une réduction régulière et considérable. Le PAR est augmenté dans certains cas (Figure 8b), mais ceci est due à une réduction plus importante de la charge moyenne dans le transformateur, ce qui s'avère aussi positive pour le réseaux.

5 Allocation dynamique de phase pour l'équilibrage du réseaux électrique

Les marchés locaux de l'énergie ont été proposés dans la section précédente comme une solution pour intégrer le nombre croissant de panneaux photovoltaïques résidentiels (PV). Cependant, comme la plupart des mécanismes de gestion de la demande, le programme fourni par ces marchés ne tient pas compte des phases auxquelles les ménages sont connectés, ce qui crée une répartition inégale des flux entre les phases. De telles dégradations du déséquilibre réseau favorisent des augmentations/-baisses de tension plus importantes, augmentent les pertes de ligne [19] et affectent fortement la durée de vie des charges triphasées. Le déséquilibre du réseau est mesuré en utilisant le facteur de

déséquilibre de tension (VUF), qui doit être maintenu sous 2% comme l'une des principales mesures de qualité de service.

Le but de cette section est de proposer et d'évaluer des mécanismes permettant de profiter de tous les avantages du marché local sans souffrir des problèmes mentionnés. Nous proposons de combiner les marchés locaux avec un changement de phase dynamique, en ré-allouant quelques ménages aux phases chaque fois que le marché local décide des flux à échanger. En particulier, nous proposons des mécanismes rentables pour la sélection des ménages à changer et pour leur allocation optimale aux phases. La solution est basée sur des commutateurs à semi-conducteurs (Solid-state Transfer Switches (STS)) installés au point de couplage commun (Point of Common Coupling (PCC)) de certains acteurs du marché.

5.1 Description du système

Le système à l'étude est similaire au système considéré dans la section précédente, où les ménages échangent de l'énergie et des services via les marchés énergétiques locaux. Dans la présente section, nous utilisons les données obtenues du marché pour répartir dynamiquement les ménages en phases (Section 1) en utilisant des commutateurs STS (Section 1).

Allocation dynamique de phases

La solution traditionnelle au déséquilibre de réseau est de ré-allouer les phases de certaines maisons monophasées en fonction de leurs profils de charge moyennés sur de longues périodes. Cela nécessite un technicien pour commuter manuellement les connexions de phase, ce qui implique des coûts élevés et aucune adaptabilité. Pour ces raisons, une telle approche statique n'est appliquée que lorsque le Voltage Unbalance Factor (VUF) est proche de 2%. L'objectif de la commutation de phase dynamique est de neutraliser l'effet négatif des marché locaux et d'augmenter la capacité d'hébergement de la grille, plutôt que de réaffecter les phases uniquement lorsque la VUF atteint des valeurs critiques. Le déploiement des commutateurs peut se faire progressivement en sélectionnant les ménages suivant le mécanisme proposé dans la Section 1. Les commutateurs sont actionnés toutes les 10 minutes comme décrit dans la Section 1, basée sur les résultats de marché et l'état de connexion de phase[7].

Commutateurs de phase à semi-conducteurs

L'implémentation proposée pour les commutateurs de transfert de phase est composée de trois commutateurs Si-IGBT [8], un pour chaque phase, trois contacteurs mécaniques et un contrôleur mettant en œuvre un verrouillage logique. Ces décisions de conception garantissent que les charges ne seront pas affectées par les commutations [20], les courts-circuits sont évités grâce à l'inter-verrouillage et les commutateurs sont protégés contre les défauts grâce aux contacteurs mécaniques. Les signaux de contrôle sont envoyés via l'infrastructure de comptage avancée et arrivent au STS par la TIC [21] ou BlueTic [22].

5.2 *Related Work*

La plupart des mécanismes d'ordonnancement ne prennent pas en compte la phase à laquelle les ménages sont connectés et ceux qui le font (p. ex. : basée sur le flux de puissance optimal asymétrique triphasé [23]) nécessitent des calculs complexes et des connaissances détaillées sur la structure du réseau. Les propositions précédentes de changement de phase dynamique [19, 20, 24] ne tiennent pas compte des énergies renouvelables, qui ont un impact majeur sur le déséquilibre du réseau et les déviations de tension, requièrent le déploiement des points de mesure et/ou demandent au ménages, qui n'ont pas d'intérêt à partager des informations véridiques[9], de partager périodiquement

[7] Notez qu'avec les compteurs intelligents, nous avons accès aux informations de connexion de phase.
[8] Interlocked Insulated-Gate Bipolar Transistor.
[9] Dans notre travail, un marché local des échanges d'énergie incite les ménages à révéler l'information véridiquement.

des informations sur les flux échangés avec la grille [20]. De plus, les mécanismes existants visent une recherche étendue assumant que toutes le maisons sont équipées avec des commutateurs. Au lieu de cela, notre approche consiste à trouver des algorithmes simples qui permettraient des réductions considérables de VUF, avec un ensemble réduit de commutateurs et avec des exigences minimales d'information.

5.3 Modèle d'allocation dynamique de phase

Allocation de phase

Soit $\mathcal{H}$ l'ensemble des ménages H sur une réseau de distribution BT, à partir de laquelle un sous-ensemble $\mathcal{M}$ participe sur le marché local. Les maisons dans $\mathcal{M}$ sont éligibles pour l'installation d'un commutateur formant un ensemble $\mathcal{E} \subset \mathcal{M} \subset \mathcal{H}$ de taille E. Notons les maisons avec des phases statiques de $\mathcal{N}$ de taille $N = H - E$. Une allocation de phase peut être vue comme un graphe biparti formé par l'ensemble des ménages et l'ensemble des phases, avec une matrice d'adjacence booléenne $X \in \mathbb{B}^{3\times H}$ où son élément $x_{i,j}$ est 1 si le ménage j est connecté à la phase i, et 0 sinon.

Choix des ménages à transférer

Dans cette section, nous proposons des heuristiques simples pour choisir les maisons où installer les commutateurs. Nous proposons des mécanismes qui reposent uniquement sur les informations déjà disponibles pour le DSO.

***Mean Based* (MB) -** Les maisons sélectionnées par le mécanisme MB sont celles pour lesquelles un DSO exécutant une allocation de phase statique déciderait de changer de phase, sur la base de charges moyennes à long terme.

***Highest Average Flow* (HAF) -** Pour HAF, nous pré-sélectionnons d'abord les maisons avec PV affectées à la phase avec la tension la plus élevée et les ménages sans PV affectés à d'autres phases, de préférence celui avec la plus basse tension. Ceci vise à réduire la production sur la phase avec la plus haute tension et / ou à réduire la consommation sur la phase avec la plus basse tension. Ensuite, nous choisissons le / les flux ayant le débit moyen le plus élevé (respectivement l'injection et la demande), afin de minimiser le nombre de transferts de phase requis pour équilibrer les flux entre les phases.

Hybride - Dans l'approche hybride, MB est utilisé pour une présélection et HAF pour l'obtention de l'ensemble final de candidats.

Allocation dynamique de phase

Nous proposons de minimiser l'impact négatif des acteurs participant au marché. Cela nécessite que les flux imposés par ces acteurs soient aussi équilibrés que possible entre les phases. Soit e l'ensemble des engagements des ces acteurs, pour le créneau horaire en question, sur le départ correspondant, nous visons à obtenir une allocation de phase de l'ensemble des commutateurs $\mathcal{E}$ tel que le flux imposé par les participants du marché $\mathcal{M}$ sur chaque phase soit le plus proche que possible de la moyenne $e_m = \frac{e}{3}$. Pour cela, une métrique naturelle à minimiser est la distance des moindres carrés (*Least squares*) des flux correspondants. Le vecteur binaire $x = [x^a, x^b, x^c]^T \in \mathbb{B}^{3M}$ représente l'allocation de phase des participants telle que $X = [x^{a\,T}, x^{b\,T}, x^{c\,T}] \in \mathbb{B}^{M\times 3}$ est la matrice d'adjacence du graphe d'allocation de phase correspondante. Ensuite, le problème à résoudre est

$$min_x ||\overline{e} - P^T x||^2 \tag{7}$$

s.t.

$$x^a + x^b + x^c = \mathbf{1} \tag{8}$$

$$x^0 x^T = N \tag{9}$$

$$x_i \in 0, 1, \forall i \in \{1, \ldots, 3M\} \tag{10}$$

où $\overline{e} = [e_m, e_m, e_m]^T \in \mathbb{R}^3$, et $P \in \mathbb{R}^{3M \times 3}$ est une matrice diagonale de bloc formé à partir du vecteur des engagements des participants $p_c \in \mathbb{R}^M$, tel que le produit $P^T x$ désigne le vecteur des flux agrégés sur les 3 phases pour une allocation de phase donnée x . La contrainte (8) garantit qu'une seule allocation par maison est donnée, où $\mathbf{1}$ désigne le vecteur unitaire de taille M. La contrainte sur la distance de Hamming entre x^0 et x en (9) garantit que les maisons de l'ensemble $\mathcal{N}$ conserveront leurs allocations de phase, avec x^0 représentant l'allocation de phase actuelle, mais avec des zéros sur les éléments correspondant à $\mathcal{E}$. Ce problème peut être classé en tant que *Mixed Integer Least Squares* (*Mixed Integer Quadratic Program*) et exprimé comme suit

$$\min_x x^T Q x + f^T x \tag{11}$$

s.t.

(8) − (10)

où Q et f peuvent être exprimés en fonction des paramètres du problème original (7) comme suit : $Q = P^T P$ et $f = -P\overline{e}^T$.

5.4 Simulations et résultats

Scénarios système

Le processus d'évaluation comporte deux parties. Tout d'abord, dans la Section 1, nous évaluons les performances de la commutation de phase dynamique par rapport à la statique. Pour cela, nous considérons un scénario avec un déploiement massif de DER et la même quantité de transferts et commutateurs de phase pour les approches statiques et dynamiques respectivement. Dans ce cas, nous considérons $H = 33$ ménages, 8 sans flexibilité (environ $H/4$), 8 avec batterie seulement (environ $H/4$) et 17 avec PV et batterie (environ $H/2$).

Ensuite, dans la Section 1, nous évaluons l'adaptabilité des approches statiques et dynamiques à mesure que nous évoluons vers un déploiement massif de DER, représenté par quatre scénarios consécutifs avec 50 maisons :

- Scénario A : 20% stockage and 30% renouvelable.
- Scénario B : 40% stockage and 40% renouvelable.
- Scénario C : 60% stockage and 50% renouvelable.
- Scénario D : 60% stockage and 80% renouvelable.

Paramètres de simulation

Nous nous appuyons sur DisNetSimPl pour les études de *load flow* avec une version légèrement modifiée du modèle de réseau électrique fourni dans [HKMS17] et avec les paramètres suivants :
Profils de demande - 6 jours de consommation de 50 maisons (SMACH [25]).

Profils de production - Production synthétique égale pour toutes les maisons.

Batteries - Des batteries idéales d'une capacité de 6 kWh.

Prix de l'électricité - *Time Of Use* à deux niveaux : 15 c€€/kWh de 12h00 à 16h00 et 20 c€ /kWh de 17h00 à 23h00.

Résultats et discussion

Analyse d'impact

Nous analysons d'abord l'impact des transferts de phase sur les avantages des interactions locales du marché de l'énergie en ce qui concerne l'énergie passant par le transformateur, les pertes correspondantes sur le transformateur et les réductions de la charge de pointe. Les avantages du marché de l'énergie local sont maintenus pour les mécanismes de commutation de phase testés. Comme prévu, ces paramètres sont à peine affectés par la commutation de phase, car tous sont des mesures agrégées de la charge et des pertes au niveau du transformateur.

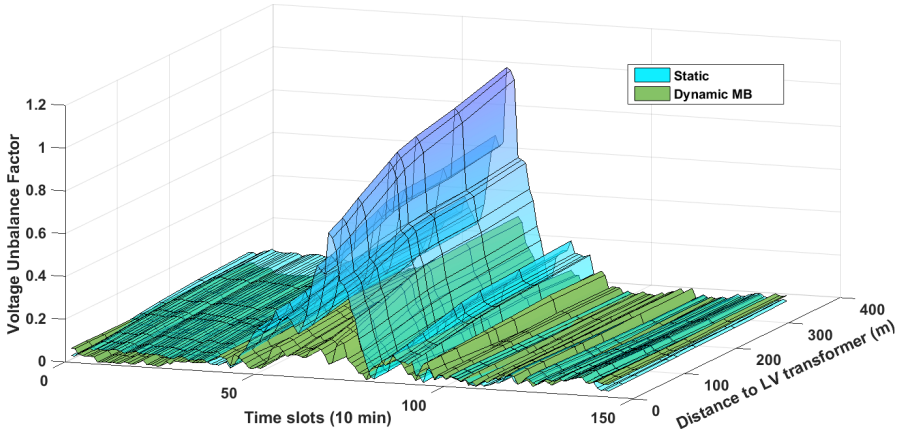


FIGURE 9 – Variation du VUF au long du départ le plus chargé.

Ensuite, nous analysons la performance des mécanismes de transfert de phase sur la réduction de du VUF maximale et l'impacte des RES sur le déséquilibre. Dans la Figure 9, nous montrons la variation des valeurs de VUF dans le temps pour le jour 1 au long du départ le plus chargé. La comparaison est faite pour quatre transferts/commutateurs de phase, avec 3 étant effectués/installés dans le départ le plus chargé, suivant les approches statique et Dynamique MB respectivement. La figure illustre la forte influence de la production renouvelable et de la commutation de phase sur le déséquilibre de tension, par la forme des deux superficies et par leur écart à niveau du pic respectivement.

Analyse d'adaptabilité

Nous analysons ensuite l'adaptabilité de notre solution de commutation de phase dynamique par rapport à la commutation statique selon des scénarios représentant un développement possible d'une réseau de distribution résidentielle dans les années à venir (Section 1). Nous comparons la quantité de commutateurs de phase nécessaires pour obtenir une réduction du pic VUF par rapport à un scénario sans marché.

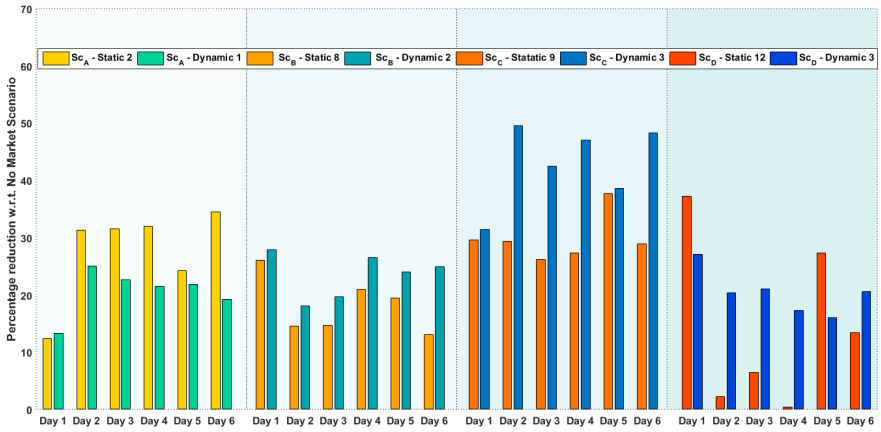


FIGURE 10 – Réductions du VUF avec des commutateurs de phase dans 6% des maisons.

Dans la Figure 10 nous observons la réduction du pic VUF qui est obtenue avec le nombre minimum de commutateurs de phase nécessaires pour contrer l'effet négatif des mécanismes de planification pour tous les jours et tous les scénarios. Les scénarios sont représentés par des zones ordonnées de A à D, les couleurs jaune à rouge représentent l'approche statique, tandis que les vertes à bleues représentent des résultats dynamiques. Pour l'approche statique, 12 transferts de phase sont nécessaires (2 dans le scénario A, 6 dans B, 1 dans C et 3 dans D), tandis que pour l'approche dynamique seulement 3 sont suffisants (1 dans A, B et C), ce qui représente 24% des ménages contre seulement 6% pour le cas dynamique.

Par rapport aux déviations de tension, si nous installons 6 commutateurs dynamiques (2 en A, 2 en C et 2 en D), ce qui représente 12% du total des ménages, nous obtenons sans exceptions une performance supérieure. Par exemple, les déviations de tension obtenus au scénario D (80% d'énergies renouvelables) avec notre système sont inférieurs à ceux obtenus dans le scénario C (50% d'énergies renouvelables) pour un scénario sans marché, tout le reste étant égale. La même chose vaut pour le scénario C par rapport aux scénarios A et B. Cela représente une augmentation considérable de la capacité d'accueil en ce qui concerne l'augmentation/baisse de tension.

Enfin, en ce qui concerne les pertes, la commutation de phase dynamique surpasse la performance de l'approche statique avec moins de la moitié des déploiements de techniciens. Les avantages économiques obtenus à partir de la réduction des pertes pourraient suffire à financer le déploiement de commutateurs. Suivant une estimation très approximative des dites économies on obtient un résultat de plus de 300 € pour le déploiement de chaque appareil, ce qui n'est pas négligeable.

6 Réalisation des décisions du marché en temps réel

Les marchés introduits dans la Section 1, ainsi que la plus partie des mécanismes de gestion de l'énergie qui reposent sur des accords de type ex-ante (*day-ahead*, *hour-ahead*, etc.), impliquent que les agents souscrivent des engagements sur les flux énergétiques futurs. Néanmoins, ces flux ne peuvent être prévus avec une grande précision en raison de leur dépendance au comportement humain et de variables exogènes contrôlées par la nature (température, ensoleillement et vent). Ainsi, pour faire face à l'incertitude de la demande et de la production locale renouvelable, un contrôle en temps réel des ressources énergétiques doit fournir les moyens de conduire les ménages vers un échange final avec le réseau qui profite à la fois aux prosumer et aux DSO.

Dans cette section, nous abordons le contrôle des flux d'électricité sur un réseau de distribution

basse tension résidentiel en temps réel. Nous proposons un modèle de théorie des jeux qui permet aux ménages de décider quels flux d'électricité échanger avec le réseau de distribution afin de minimiser leurs coûts. Ces coûts dépendent de la stratégie moyenne de tous les ménages et également d'un signal de pénalité associé à une contrainte de couplage. Ce jeu agrégatif permet aux ménages d'optimiser leurs propres coûts tout en réduisant les hausses/chutes de tension et les flux de courant sur les lignes.

6.1 *Related Work*

Nous nous concentrons sur la littérature relative au contrôle en temps réel des flux d'électricité sur les réseaux de distribution. Plusieurs approches centralisées ont été proposées pour la gestion de l'énergie en temps réel des réseaux de distribution [26–28]. La difficulté de telles approches est que les DER flexibles sont détenues et contrôlées par les ménages, qui détiennent les informations locales nécessaires pour un contrôle centralisé et ne diffuseront une partie de ces informations que si des incitations adéquates sont fournies. Dans [29] et [30], les auteurs proposent des mécanismes décentralisés dans le but d'aplatir la demande agrégée d'une large population d'agents représentant les ménages. Ils ne prennent pas en compte les RES distribués et les contraintes DSO non plus.

La théorie des jeux a été appliquée principalement à l'ordonnancement énergétique journalier, et en particulier à la modélisation des interactions entre l'*utility*/fournisseur et ses clients dans le but de minimiser les coûts énergétiques [31–35]. La littérature relative au contrôle en temps réel des flux d'électricité sur les réseaux de distribution ne prend pas en compte les RES et les ressources de stockage ou ne prend pas particulièrement en compte les déviations de tension ou les contraintes thermiques.

6.2 Description du système

Le système à l'étude est similaire à celui étudié dans les sections précédentes, où les ménages s'accordent sur l'échange d'énergie entre eux à travers un marché local de l'énergie tel que décrit dans la Section 1. Les marchés sont combinés avec le changement de phase dynamique (Dynamic Phase Switching (DPS)) comme décrit dans la Section 1 pour équilibrer la charge entre les phases. Ensuite, un mécanisme de contrôle en temps réel (Real-Time Control (RTC)) décrit dans la Section 1 gère les erreurs de prévision en conduisant les ménages vers un échange final avec le réseau qui profite au prosumer et qui respecte les exigences de qualité de fourniture.

Mécanisme de contrôle en temps réel

Juste avant le début de chaque intervalle de temps, les prosumers mettent à jour leur prévision pour les 10 prochaines minutes et décident jusqu'à quel point l'erreur sera absorbée par leur budget de flexibilité[10] ou par le fournisseur d'électricité. S'appuyer sur la flexibilité a un impact sur la dégradation de la batterie (ou du confort), tandis que ne pas respecter les quantités engagées dans le marché implique la perte d'une partie de la récompense ainsi que du prix avantageux. Les coûts de la flexibilité supplémentaire, du prix final de l'électricité et de l'attribution des récompenses sont décrits dans les Sections 1, 1 et 1 respectivement. De plus, pendant les créneaux horaires de forte excès de production ou de demande, les ménages seront facturés une pénalité fixée par le DSO, associée à une contrainte sur le débit moyen que l'ensemble des voisins échangent avec le réseau. Un tel signal de prix permet au DSO d'influencer la décision des ménages vers un échange final avec le réseau qui réduit les déviations de tension et le courant sur les lignes.

6.3 Modèle

Nous considérons un ensemble d'agents compétitifs $\mathcal{H} = \{1, 2, \ldots, H\}$ représentant des prosumers et un ensemble $\mathcal{N} = \{1, 2, \ldots, N\}$ de nœuds logiques sur le départ, où les connexions de plusieurs

[10] L'optimisation des offres du marché limite l'utilisation de la batterie selon des contraintes à niveau des cycles et du profondeur de décharge. Le budget de flexibilité est la capacité énergétique supplémentaire réservé pour absorber les erreurs de prévision en temps réel.

ménages sont agrégées[11], référencés comme des points de couplage commun (PCC). Un ménage est connecté à un seul PCC.

État des agents

L'état des agents est composé des prévisions de la demande et de la production, des quantités échangés sur le marché local et de l'état de la batterie au début du créneau horaire actuel, déterminé par l'état de charge (State of Charge (SoC)) et par les quantités de charge/décharge accumulées. Pour chaque agent $i \in \mathcal{H}$, le mécanisme de marché a programmé que l'utilisation de la batterie pour l'intervalle de temps courant soit $\hat{s}^i$, afin d'échanger $\hat{x}^i = \hat{x}^i_m + \hat{x}^i_u$ avec le réseau, où $\hat{x}^i_m$ et $\hat{x}^i_u$ sont les montants échangés avec voisins et avec le fournisseur respectivement, sous un gap prévu $\hat{r}^i$ entre la production $\hat{g}^i \in \mathbb{R}^N_{\geq 0}$ et la consommation $\hat{l}^i \in \mathbb{R}^N_{\geq 0}$ selon l'équation d'équilibre suivante

$$\hat{x}^i_m + \hat{x}^i_u + \hat{s}^i = \hat{l}^i - \hat{g}^i = \hat{r}^i \tag{12}$$

Une prévision plus proche du temps réel ou une *Very Short Term Load Forecast* [36] permet à chaque maison de mettre à jour son écart entre la consommation et la production comme $r^i = \hat{r}^i + \tilde{r}^i$, où $\tilde{r}^i = \tilde{l}^i - \tilde{g}^i$ est l'erreur sur les prévisions de production et de charge horaire.

Stratégies des agents

Le contrôle en temps réel de chaque ménage vise à déterminer dans quelle mesure l'erreur $\tilde{r}^i$ sera absorbée par le réseau ou par la flexibilité de la demande. Ainsi, chaque agent i décide d'une stratégie (x^i, s^i), où $s^i \in \mathbb{R}^N$ représente la quantité d'énergie chargée (négative) ou déchargée (positive) vers/depuis les batteries et $x^i \in \mathbb{R}^N$ est la quantité totale d'énergie à échanger avec le réseau sur l'intervalle de temps correspondant.

Batteries

La quantité d'énergie stockée dans la batterie du ménage i à la fin de l'intervalle de temps courant est représentée par $e^i \in \mathbb{R}^N$. Son évolution dans le temps est donnée par $e^i = e^i_0 - s^i$, où e^i_0 représente l'énergie de la batterie au début de l'intervalle de temps actuel. Le fonctionnement des batteries ou des charges flexibles doit respecter la contrainte suivante :

$$\max[e^i_0 - \overline{E}^i, \underline{s}^i, \underline{e}^i] \leq s^i \leq \min[e^i_0 - \underline{E}^i, \overline{s}^i, \overline{e}^i] \tag{13}$$

qui limite l'utilisation de la batterie à l'intersection de trois segments :

Capacité d'énergie La batterie ne peut pas être déchargée ou chargée au-delà de son niveau d'énergie minimum ou maximum, respectivement $\underline{E}^i$ et $\overline{E}^i$ (fixées généralement autour de 10-20% et 80-90% du SoC respectivement).

Capacité de puissance représente l'énergie minimum et maximum qui peut être échangée avec la batterie sur un créneau temporel, $\underline{s}^i$ et $\overline{s}^i$ respectivement.

Capacité de Cyclage $\underline{e}^i$ et $\overline{e}^i$ représentent les contraintes des cycliques de chargement et de déchargement.

Pour les batteries fonctionnant sous de telles contraintes, les coûts de dégradation sont exprimés

$$C^i_e(s^i) = a^i(s^i - \hat{s}^i)^T(s^i - \hat{s}^i) + {b^i}^T(s^i - \hat{s}^i) \tag{14}$$

[11] p. ex. : où les points de mesure sont déployés ou au debout d'une branche qui alimente plusieurs ménages.

où s^i et C_e^i représentent l'utilisation de la flexibilité de la demande et ses coûts correspondants, et les paramètres a^i et b^i sont choisis de manière adéquate selon la source de flexibilité étant la batterie ou l'élasticité de la demande.

Prix définitifs de l'électricité

En ce qui concerne les prix, nous devons prendre en compte les deux composantes de l'engagement du marché de chaque agent $\hat{x}^i$, qui sont la quantité $\hat{x}_m^i$ échangée avec des voisins au prix P_m^i et la quantité $\hat{x}_u^i$ engagée avec le fournisseur au prix P_u ou au tarif d'achat (FIT) P_f selon que le *prosumer* achète ou vend. Le prix à payer pour le flux effectivement échangé x^i sera le suivant :

$$C_p^i(x^i) = (x^i - \hat{x}_m^i)p + \hat{x}_m^i P_m^i \tag{15}$$

where

$$p = \begin{cases} P_u, & \text{if } x^i >= \hat{x}_m^i, \\ P_f, & \text{else,} \end{cases} \tag{16}$$

Attribution de récompenses

L'attribution de la récompense dépend de l'écart par rapport aux quantités engagées dans le marché (une heure à l'avance) comme suit :

$$C_r^i(x^i) = a_r^i(x^i - \hat{x}^i)^T(x^i - \hat{x}^i) - R \tag{17}$$

où la valeur R est définie une heure à l'avance en tant que pourcentage de la quantité échangée.

Contrainte d'agrégation

Les stratégies des ménages sont couplées par une contrainte agrégative qui permet au DSO de favoriser une meilleure qualité de l'offre. La contrainte sur la stratégie moyenne est la suivante :

$$\underline{c} \leq \frac{1}{H}\sum_{i=1}^{H} x^i \leq \overline{c} \tag{18}$$

où $\underline{c}$ et $\overline{c} \in \mathbb{R}^N$ sont les contraintes sur les flux agrégées dans chaque PCC, qui sont définies par l'opérateur en fonction des flux attendus pour le période de temps en question. On note $\mathcal{C} \subset \mathbb{R}^N$, l'ensemble de $\frac{1}{H}\sum_{i=1}^{H} x^i$ tel que (18) est satisfait.

Cette procédure nécessite des connaissances spécifiques sur l'infrastructure du réseau (nœuds, lignes, impédances, etc.), qui ne sont pas nécessairement disponibles pour les réseaux de distribution. Ces informations peuvent être estimées en utilisant des mesures de l'injection de puissance et des variations de tension et de courant à différents points du réseau [37–42].

Définition du problème

Le but de chaque agent $i \in \mathcal{H}$ est de trouver une stratégie (x^i, s^i) telle que

$$x^i \in \arg\min_y \; J^i\left(y, \tfrac{1}{H}\left(\textstyle\sum_{j=1}^{H} x^j\right), \lambda\right) \tag{19}$$

s.t.

(12)

(13)

$$y \in [-\overline{x}^i, \overline{x}^i] \tag{20}$$

où J^i est la fonction de coût local qui dépend de la moyenne des stratégies de tous les agents et de λ qui représente une pénalité associée à la contrainte de couplage dans (18). Le paramètre $\overline{x}^i$ dans la contrainte (20) représente l'énergie correspondant à la capacité de puissance maximale contractée avec le fournisseur par le ménage i. On note $\mathcal{X}^i$ l'ensemble des valeurs possibles de x^i.

La fonction de coût $J^i : \mathbb{R}^N \times \mathbb{R}^N \to \overline{\mathbb{R}}$, avec $\overline{\mathbb{R}} := \mathbb{R} \cup \infty$ est défini comme suit :

$$J^i(x^i, u) = f^i(x^i) + u^T x^i \tag{21}$$

où la fonction $f^i(x^i) = C_e^i(x^i) + C_r^i(x^i) + C_p^i(x^i)$ reflète les coûts qui ne dépendent que de la stratégie individuelle (dégradation de la batterie, récompense, et prix final de l'électricité) et u est un signal de contrôle diffusé (via la plateforme transactionnelle) par le DSO, qui dépend de la stratégie moyenne des maisons et de λ, pénalité associée à la contrainte de couplage dans (18).

6.4 Jeu agrégatif compétitif

Le problème décrit ci-dessus forme un jeu agrégatif compétitif, car la réponse optimale d'un agent dépend de la réponse globale du reste des joueurs et ils partagent tous une pénalité commune associée à une contrainte de couplage. Grammatico a prouvé dans [43] qu'un tel jeu a un équilibre agrégatif sous des hypothèses sur les fonctions $\{f^i\}_{i=1}^H$ étant l-fortement convexe et sur la compacité, convexité et *Slater's qualification* [44] des ensembles $\{\mathcal{X}^i\}_{i=1}^H$ et $\mathcal{C}$.

Processus itératif

Un équilibre agrégatif peut être atteint en suivant l'approche semi-distribuée proposée par Grammatico [43, Section III]. Le mécanisme repose sur le fait que les ménages répondent de manière optimale au signal d'incitation u. Le processus itératif pour atteindre un équilibre agrégatif commence au début du créneau temporel de 10 minutes avec une période d'environ 10 secondes[12], Ce qui devrait permettre aux ménages de s'adapter aux changements de pénalité, tout en fournissant suffisamment d'itérations pour que l'algorithme semi-distribué converge vers l'équilibre. Au début de l'itération k-th, l'opérateur va estimer la réponse optimale agrégée $\mathcal{A}(u_{(k-1)})$ à l'itération précédente en mesurant les flux sur chaque PCC du départ correspondant. Ensuite, il mettra à jour le signal $u_{(k)} = \kappa(t, u_{(k-1)})$, en utilisant la loi de contrôle dynamique κ proposée dans [43, Section III] . Le signal atteindra alors les *prosumers* à travers le prochain bloc publié sur la plateforme transactionnelle A la détection d'un changement de signal u, chaque agent procédera à la mise à jour de sa réponse optimale $x_{(k)}^{i*}$, en mettant à jour son flux optimal de batterie $s_{(k)}^{i*}$ à partir de (12).

A chaque itération, les *prosumers* décident du flux d'énergie à échanger avec le réseau sur l'ensemble des 10 minutes, en se basant sur la perfection des prévisions faites au début du créneau et sur les mesures de flux d'énergie et d'utilisation de la batterie jusqu'à l'itération actuelle. La procédure

Algorithm 1 Contrôle dynamique des réponses compétitives optimales [43]

Initialisation : $t \leftarrow 0$;
- Le DSO choisit $u_{(0)}$;

Itérer jusqu'à la convergence :
- DSO diffuse $u_{(0)}$ à tous les agents

  ◦ Chaque agent $i \in \mathcal{H}$ calcule $x^{i*}(u_{(t)})$,
  ◦ et définit le réglage de la batterie pour le reste de la plage horaire.

- DSO mesure la meilleure réponse moyenne $\mathcal{A}(u_{(t)})$,
- obtient $u_{(t+1)} = \kappa(t, u_{(t)})$

$t \leftarrow t + 1$

d'itération vers un équilibre agrégatif est résumée comme suit

6.5 Simulations et résultats

Procédure et scénario système

La simulation du mécanisme de contrôle en temps réel repose sur les résultats du marché de l'énergie local et sur une allocation des ménages aux phases mises à jour par un mécanisme DPS. Ces deux mécanismes supplémentaires sont simulés en suivant les procédures décrites respectivement dans [HKMS17] et [HKMC18].

Nous considérons que la prévision utilisée par les ménages pour participer au marché est une prévision de persistance journalière et que la prévision mise à jour juste avant le créneau horaire est parfaite, ce qui nous permet d'appliquer un modèle déterministe.

En ce qui concerne la période de surveillance, le mécanisme RTC n'est lancé que si pendant le créneau précédent nous avons détecté une déviation de tension de 9% ou un courant supérieur à 70% de la limite thermique. Pour simuler une telle surveillance, nous réalisons des études de flux de charge pour chaque créneau horaire en heures de pointe, et lorsqu'un risques est détecté le mécanisme RTC est lancé.

Nous considérons une réseau de distribution composée d'un départ avec 50 foyers dont 60% sont équipés d'une batterie et 80% d'un panneau PV. Tous les ménages participent sur le marché et sont éligibles au DPS. En ce qui concerne le niveau d'agrégation des ménages sur chaque PCC logique, nous considérons un PCC par phase du *feeder*. Cela signifie que toutes les maisons connectés à une même phase sont considérées comme partageant le même PCC logique. Cela permet de garder le modèle simple et indépendant de la structure physique du réseau. De plus, il n'est pas nécessaire de déployer de nouveaux points de mesure.

Outils de simulation et paramètres

Pour implémenter le mécanisme décrit dans l'Algorithme 1, nous utilisons MATLAB [45] avec la suite d'optimisation Gurobi [46]. Pour l'analyse du flux de puissance, nous nous appuyons sur DisNetSimPl et sur un modèle de réseau électrique formé par un transformateur de 20 kV/410 V et 160 kVA, et une alimentation avec des lignes électriques en aluminium de 70 mm2. Les paramètres utilisés pour les simulations étaient les suivants :

Profiles de demande - Courbes de charge de 50 ménages pour 7 jours d'hiver (SMACH [25]).

[12] Notez que le temps entre blocs sur la plateforme transactionnelle basée sur blockchain décrite dans [HKMS17] est d'environ 5 secondes.

Profils de production - Même courbe de production synthétique pour tous les panneaux PV (tous situés sur la même zone), mais le profil varie quotidiennement.

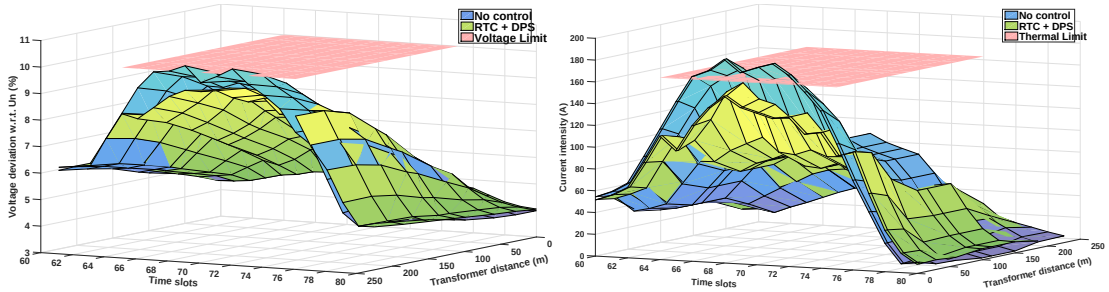
Batteries - Nous considérons les batteries idéales de 9kWh de capacité totale. Jusqu'à 6 kWh (10% à 77%) peuvent être utilisés pour les échanges sur le marché local tout en réservant une part de la capacité (1,2 kWh) au mécanisme RTC, qui peut utiliser jusqu'à 7,2 kWh (10% à 90 %) de la capacité et effectuer un cycle supplémentaire pour absorber les erreurs de prévision. Pour le cas des appareils flexibles, dont l'élasticité est entièrement réservée au mécanisme RTC, nous considérons que jusqu'à 1 kWh d'énergie est disponible pour faire face aux erreurs de prévision.

Tarifs de l'électricité - *Time of Use* à deux niveaux : 15 c€ /kWh de 12h à 16h et 20c€ /kWh de 17h à 23h. Alors que le FIT est considéré comme 10c€ /kWh.

Résultats et discussion

Nous analysons la performance du mécanisme RTC au cours des créneaux horaires à forte production d'énergie renouvelable (entre 10h et 14h). En particulier, nous nous intéressons aux cas où nous observons que les limites thermiques ou de tension sont dépassées, ou proches des limites, pour le scénario sans RTC. A partir des 7 jours analysés sur les simulations, nous nous concentrons sur le jour le plus critique, à la fois en termes de déviations de tension et de flux de courant. Dans un premier temps, nous analysons les écarts de tension par rapport à la valeur nominale puis la réduction des flux de courant sur les lignes. Dans les deux cas, nous comparons le mécanisme RTC couplé à DPS à un cas sans incitations en temps réel et sans changement de phase, dans lequel la seule différence pour l'optimisation des ménages est que le signal u est 0 pour tous les créneaux temporels.

Réduction des écarts de tension - Nous commençons par analyser l'impact du mécanisme RTC dans les déviations de tension par rapport à la valeur nominale Un. Dans la Figure 11a, nous voyons les déviations de tension le long du *feeder* pour le mécanisme RTC couplé avec DPS, comparé au cas sans RTC, qui sont représentés par deux surfaces, vert et bleu respectivement. La surface rouge (planaire) montre la limite de tension pendant la période où le RTC était actif. Pendant cette période, le mécanisme RTC combiné au DPS réalise des réductions réguliers des déviations de tension maximales, observées lorsque la surface verte (RTC + DPS) passe sous la surface bleue, tandis que pour le cas sans RTC, les limites de tension sont violées deux fois, quand la surface bleue va au-dessus de la surface rouge. Ces résultats démontrent la capacité de RTC combiné avec DPS pour éviter les dépassement des contraintes de tension.



(a) Déviations de tension maximales. (b) Niveau d'intensité électrique.

FIGURE 11 – Intensité électrique et déviations de tension au long du *feeder*.

Réduction des flux de courant à travers les lignes - En ce qui concerne les flux de courant à travers les lignes, dans la Figure 11b nous montrons l'intensité du courant le long du *feeder* pendant la période de surveillance. La surface rouge (planaire) montre la limite thermique pendant la période où le RTC était actif. Pendant cette période nous pouvons clairement apprécier des réductions considérables de l'intensité du courant tout au long du *feeder* en évitant le dépassement des contraintes thermiques qui sont observées pour le cas sans RTC. De telles réductions sont suffisantes pour éviter ou retarder le remplacement de segments de ligne entiers, ce qui se traduit directement par une réduction considérable des investissements dans les infrastructures.

7 Conclusions générales et travaux futurs

Le secteur de l'électricité est en pleine évolution, notamment en raison du déploiement local des sources d'énergie renouvelable et de la capacité de stockage, qui constituent un moteur essentiel de la transition énergétique et des objectifs connexes. Néanmoins, les réseaux de distribution d'électricité actuels n'ont pas été conçus pour faire face à un déploiement massif de sources d'énergie renouvelables sur des sites résidentiels, ni pour les changements structurels de charge induits par la croissance rapide attendue du marché de la voiture électrique. Les transformations nécessaires du réseau de distribution retardent aujourd'hui, et dans certains cas bloquent, la possibilité de tirer parti de ces opportunités. Les mécanismes de gestion de la demande peuvent jouer un rôle clé dans l'intégration des ressources énergétiques distribuées, mais en l'absence de changements architecturaux permettant d'exploiter la flexibilité de la demande, les investissements requis pour le renforcement des infrastructures peuvent être extrêmement élevés.

Dans cette thèse, nous proposons une architecture innovante et rentable capable de favoriser la collaboration entre les acteurs du marché de gros, les opérateurs de systèmes de distribution et les clients finaux (qui deviennent *prosumers*). L'architecture est conçue pour fournir des services novateurs de gestion de la demande résidentielle, avec un accent particulier sur l'autoconsommation au niveau des ménages et des quartiers. Nous montrons que l'architecture et les mécanismes de gestion de la demande associés que nous proposons permettent de réduire la congestion, de réduire les déviations de tension et les pertes et, par conséquent, d'augmenter la capacité du réseau de distribution d'accueillir l'énergie renouvelable. Cela a été validé par des simulations utilisant l'analyse de flux de puissance avec des profils de charge réalistes, fournissant des informations précieuses pour la conception des futures architectures de réseau de distribution et des systèmes de gestion de l'énergie.

Dans la partie II de la thèse, nous proposons les éléments constitutifs des futures architectures de gestion de l'énergie du réseau de distribution. Dans le Chapitre 2, nous proposons les composants fonctionnels et technologiques pour la mise en œuvre d'une architecture de maison intelligente basée sur l'Internet des Objets. Nous mettons l'accent sur les problèmes d'interopérabilité et d'orchestration. Dans le Chapitre 3, nous étendons cette architecture de la maison au niveau du quartier, en proposant le concept de réseau virtuel de distribution et, de façon complémentaire, nous introduisons les composants permettant de déployer une infrastructure blockchain pour permettre les differents acteurs dans un quartier d'échanger des blocs d'énergie et de services de façon autonome, sécurisé, rentable et transparente.

Dans la partie III, qui contient les principales contributions de la thèse, nous proposons des services et mécanismes innovants rendus possibles par l'architecture et montrons leur impact positif sur la capacité des réseaux de distribution à accueillir des énergies renouvelables tout en maintenant la qualité de l'approvisionnement en électricité.

Dans le Chapitre 4, nous proposons un marché qui permet aux ménages d'échanger de manière autonome des blocs énergétiques avec leurs voisins et avec d'autres acteurs du marché. Le système proposé est basé sur un mécanisme d'enchères et des réductions de frais de transport dynamiques,

conçus conjointement pour inciter les ménages à gérer localement les ressources énergétiques de manière à favoriser l'équilibre entre la production d'énergie renouvelable et la demande flexible au niveau du quartier. Une évaluation approfondie de l'impacte du marché proposé montre des réductions considérables (de plus de 30%) de l'excès de production d'énergie renouvelable vers la Moyenne Tension et des réductions importantes (supérieures à 10% dans les cas pertinents) de la puissance de crête traversant le transformateur. Un avantage supplémentaire est la réduction des pertes sur le transformateur et les lignes.

Néanmoins, comme la plupart des mécanismes d'ordonnancement, le marché proposé crée de nouveaux déséquilibres dans les flux entre phases, ce qui favorise des hausses/baisses de tension plus élevées et des pertes au niveau du neutre. Dans le Chapitre 5, nous proposons d'allouer dynamiquement les ménages aux phases pour faire face à ces problèmes en coordonnant les décisions de transfert de phase avec les décisions du marché. Nous montrons que, pour un scénario de 50 ménages où 80% d'entre eux sont équipés de panneaux photovoltaïques et 60% de stockage, seul un petit nombre de ménages (6%) doivent être équipés de commutateurs de phase pour contrer les effets négatifs des marchés locaux tout en conservant tous leurs avantages. En particulière, les niveaux de déviation de tension peuvent être réduits considérablement.

Comme tous les mécanismes de type ex-ante, le marché d'énergie proposé repose sur des prévisions (d'une heure à l'avance) dont la précision peut être faible, ce qui peut sérieusement affecter ça performance. Pour faire face à ce problème, nous proposons dans le Chapitre 6 un mécanisme de contrôle en temps réel, basé sur la théorie des jeux, qui gère les erreurs de prévision en conduisant les ménages à un échange final avec le réseau qui respecte les contraintes définis par le gestionnaire. Nous avons évalué la performance du mécanisme pour un scénario avec 50 ménages dans lequel des violations des contraintes thermiques et de déviation de tension sont observés. L'application du mécanisme de contrôle en temps réel combiné avec la commutation de phase dynamique permet d'éviter complètement ces dépassements de contraintes.

En résumé, cette thèse présente une architecture générale qui facilite le développement de services innovants pour les clients à travers l'échange d'énergie et de flexibilité avec des voisins, fournisseurs de services et opérateurs de réseau. La combinaison du marché énergétique local proposé, du transfert de phase dynamique et des mécanismes de contrôle en temps réel apporte des solutions aux grands défis du réseau de distribution sans nécessiter d'investissements importants dans l'infrastructure ; permettant ainsi d'atteindre les objectifs de la thèse par rapport à augmenter effectivement la capacité du réseau de distribution à accueillir d'énergies renouvelables et de soutenir la transition énergétique.

Enfin, l'architecture générale proposée et les nouveaux services énergétiques, avec leurs mécanismes correspondants de gestion de la demande, constituent également la base des innovations futures en termes de systèmes de gestion de l'énergie et de services énergétiques connexes. Nous décrivons brièvement une sélection des perspectives les plus pertinents :

Architecture de gestion de l'énergie des réseaux de distribution - Dans le Chapitre 3, nous avons introduit deux nouveaux concepts de gestion de l'énergie du réseau de distribution : la virtualisation du réseau de distribution et la plateforme transactionnelle d'énergie basée sur la blockchain. Les travaux futurs devraient évaluer les contraintes techniques spécifiques (notamment la tension partagée entre réseaux de distribution virtuels) qui entravent la virtualisation de l'infrastructure. Si ces limitations étaient résolues, tout un ensemble de mécanismes conçus pour les réseaux de données pourrait potentiellement être appliqués pour améliorer l'allocation des ressources dans les réseaux d'électricité. En ce qui concerne la plateforme transactionnelle basée sur blockchain, il y a beaucoup de matière pour la recherche future, y compris les incitations, le passage à l'échelle, la gouvernance, le respect de la vie privée, etc. Par exemple, une alternative à la cryptomonnaie pour récompenser les *prosumers* pourrait être de créer des jetons d'escompte, avec un prix indexé au prix réglementé de l'électricité (au prorata de la valeur créée pour le réseau lors de l'émission du jeton), qui pourrait être récupéré et transformé en monnaie fiduciaire par les fournisseurs d'électricité.

Mécanismes de gestion de l'énergie - Les mécanismes de gestion de l'énergie proposés dans les Chapitres 4, 5 et 6 peuvent être étendus dans plusieurs directions, intégrant de nouvelles ressources/technologies, de nouvelles incitations et mécanismes de marché, de nouvelles stratégies et de nouveaux mécanismes d'apprentissage, etc. Par exemple, l'intégration des véhicules électriques, non seulement comme demande flexible, mais également comme source d'énergie pouvant jouer dans les marchés proposés, ainsi que d'autres technologies pouvant être massivement déployées dans le futur (capacités de stockage avancées à toutes les échelles, recharge de véhicules électriques en mouvement, etc.). Une amélioration fondamentale serait d'introduire des modèles stochastiques, permettant une meilleure modélisation de la production, de la demande et de la mobilité électrique. Cela pourrait se faire à travers de modèles de jeux stochastiques.

Mobilité électrique : facteur clé des services (énergétiques) innovants - L'une des caractéristiques distinctives de l'échange énergétique local proposé dans la thèse est la récompense de tous ceux qui participent à l'équilibrage local de la production d'énergie renouvelable. Cette récompense peut prendre la forme d'un jeton numérique qui pourrait ensuite être utilisé en échange de services énergétiques. La mobilité apparaît alors comme l'un des principaux vecteurs d'innovation, car ce jeton énergétique pourrait être utilisé pour accéder de manière transparente à des services énergétiques personnalisés indépendamment de l'endroit, comme recharger votre véhicule électrique chez un amie, sur un point de recharge public ou privé (partagé), voir même pour avoir accès au transport public.

Réseaux d'électricité du futur - Les extensions décrites précédemment fournissent les éléments nécessaires pour permettre notre vision des futurs réseaux d'électricité. Dans les futurs réseaux, les architectures transactionnelles peuvent pousser les fournisseurs d'énergie à passer de la vente d'électrons à la vente de services énergétiques différenciés, avec une qualité de service différente (par exemple en cas de congestion), avec un choix spécifique de sources d'énergie et une mobilité qui permettrait de consommer des services énergétiques personnalisés et de partager des ressources énergétiques indépendamment de l'emplacement. De telles architectures devraient permettre l'échange de services énergétiques au-delà de l'équilibrage local, tels que des services auxiliaires pour les gestionnaires des réseaux, ainsi que d'autres types de services au-delà de l'énergie. Les mécanismes pour permettre ces services ainsi que la coordination de l'utilisation de la flexibilité à des fins locales et globales font l'objet de recherches plus approfondies, pour garantir la stabilité et la fiabilité du réseau avec des mécanismes aussi complexes et corrélés, en particulier si la possibilité d'îlotage des réseaux de distribution est considérée.

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Part I

Introduction

Chapter 1

Introduction

1 Context and vision on Smart Grids

Electricity grids have for long been considered among the most complex "machines" ever built by mankind and they are meant to continue to be so as we evolve towards the Smart Grid under the context of the energy transition.

The legacy electricity grid from 10 years ago was traditionally led by a business approach where the consumer had a passive role as a subscriber of a basic service and the complete electricity conversion chain was managed and operated by a single actor. The generation of energy was concentrated in a few centralized bulk generation facilities and the flux of energy ran unidirectional towards the consumers (see Figure 1.1). The communication architecture was deployed mainly at the core of the grid to support operation and management Supervisory Control And Data Acquisition (SCADA) systems. The lack of fine grained information coming from the distribution system[1] and the lack of control at customer premises, besides the circuit breaker that could not even be triggered remotely, imposed great limitations into applications like billing or crisis management.

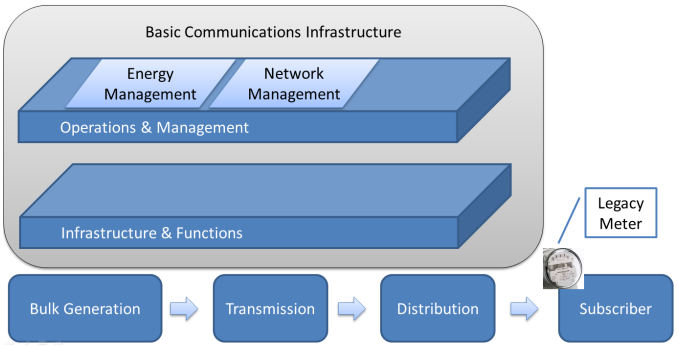


Figure 1.1 – Legacy grid.

During the last 10 years the electric grid has suffered important transformations such as the unbundling of the electricity conversion chain creating the regulated Transmission and Distribution

[1]The electricity grid is structured hierarchically into transmission grid level carrying electricity at high voltages across long distances and distribution grids that deliver medium/low voltage electricity in shorter distances.

Operators, the liberalization of wholesale and retail markets and the upcoming of new roles like Aggregators and new interactions due to European markets' integration. Reduction of CO2 emissions, capital investment deferral, operational costs reductions and energetic independence are among the main goals of the European Commission in terms of energy transition. The massive deployment of Renewable Energy Sources (RES) all along the electricity distribution chain, from centralized generation assets to local micro-generation at customer premises, together with energy demand/supply curb shaping are the key means to fulfill those objectives. However, the stochastic characteristics of these generation sources and their increasing weight in the energy mix will force the energy operators to face a paradigm change in the way they manage the grid. As generation becomes less predictable and controllable, Demand Side Management (DSM), and particularly Demand Response (DR), acquire a more important role in enforcing reliability and maintaining the quality of electricity supply. Furthermore, European Union countries are strongly promoting electric vehicles as another key strategy towards Smart Grid goals. This implies a challenge to the grid due to the increase in electricity consumption and the inherent mobility, but also a possibility for the storage capabilities that can provide flexibility[2] for balancing the grid.

This new paradigm will require a change in consumers' role from a simple subscriber to a main grid actor involved in energy production, storage, consumption shifting and trading. But not even the most committed consumer will be able to sustain such an active energy management role if it is time-consuming and complex. Therefore, to ease consumer participation, advanced communication and control technologies are needed and the definition of end user policies and any other interactions need to be few and simple. Autonomic principles will need to be applied to enforce such policies and to ease the operation and management of the system. Markets, regulation and service models must be designed to encourage consumers' active participation and involvement of new roles like Aggregators in DR solutions. This evolution in business models will drive the development of the control algorithms, management strategies and communication architectures needed to put in place advanced energy management services like DR, smart metering, distribution automation, crisis management services, etc. Our work is focused on DSM services and particularly in DR applied to distribution grid energy management. The distribution system and the customer premises are the grid domains where most of the changes are happening and where Information and Communication Technologies (ICT) community can provide further value. In Figure 1.2 we can appreciate the functionalities that are enabled by an advanced communication infrastructure. Furthermore, other domains like transmission level infrastructure management, markets evolution and the corresponding support systems are already mature and require a stronger domain specific expertise.

Information and communication technologies are the main foundation over which a control plane can be built to allow the implementation of such advanced services and technologies. In fact ICTs are the main driver for the grid to become smarter; interconnecting the devices and the actors with each other to establish transactions, acquiring and processing big amounts of information as well as expressing and delivering control signals, ICTs enable a fine grained management of the grid and the creation of value added services. Machine to Machine (M2M) automation systems, Internet of Things (IoT) architectures, Cloud computing, Cellular Networks, Blockchain-based distributed ledger technologies, Data Centric Networking and Machine Learning are some of the key technologies which have been evolving fast and can provide good support for the smart grid. Some of these technologies have already been applied to Advanced Metering Infrastructure (AMI) projects, which are seen in most cases as the first step towards a Smart Grid.

[2]Flexibility, in this context, can be defined as the capability to adapt demand and/or injection flows of electricity to the grid by adapting consumption patterns, controlling generation output or storing energy.

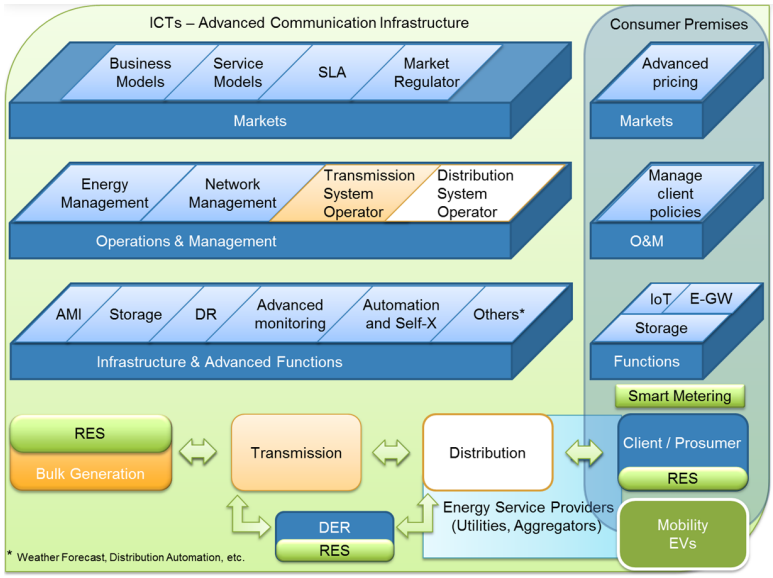


Figure 1.2 – Representation of the Smart Grid Vision.

2 Motivation

2.1 Structure of electricity Markets

Currently the French wholesale energy market has two main components, the bilateral contracts (also called Over The Counter) and a centralized trading market where the spot price is established in a day-ahead basis and the hour-ahead market enables a better grained settlement for the demand/supply balance. The real time balance is managed by RTE, the French Transmission System Operator (TSO), using three types of reserves in charge of providing the power needed to cover the imbalance between what was settled in the market and what has really been demanded/produced. The French primary and secondary reserve represent approximately 1500 MW and are built from a mandatory share of the generation facilities that must be available and react automatically in less than 30 seconds and fifteen minutes respectively. The tertiary reserve comprises a share of power fixed by contract and a share that is settled in a sort of market called "adjustment mechanism", where the only buyer is RTE. The tertiary reserve accounts for approximately 2000 MW and is called when primary and secondary reserves are not enough to solve the imbalance in terms of power or when the imbalance cannot be solved in a short time and primary and secondary reserves need to be recovered.

The role of aggregators is to offer advanced services to its customers (based on the characterization of loads) while using the aggregated flexibility to participate in the energy market and/or the adjustment mechanism helping to keep the balance of the grid. The role can be played by the utility itself or by a third party, which is currently the case in the French market . Forecasting demand is key for players of French market as the errors in demand estimation are charged by the responsible for the balance of the grid (RTE) in a price higher than the spot price (or paid lower than the spot price in the case of excess of energy). In this regard distributed storage or even the Electric Vehicles (EV) can create uncertainties for the utilities, highlighting the need for the utilities to count on information about consumption, distributed storage and generation. It is also to highlight the need for the utilities to fulfill the role of aggregators, offering services to the consumer based on their flexibility, for participating in the market or for internal use, optimizing costs and their balance as Balancing

Responsible Entities (BRE).

With respect to the distribution grid level, the increasing deployment of distributed RES, like residential solar panels attached to the distribution grid[3], and the growth in adoption of EV are posing severe challenges to the Distribution System Operator (DSO), e.g.: in terms of quality of supply, congestion, voltage variations and on the protection system. In order to cope with these challenges DSOs will increasingly rely on flexible[4] Distributed Energy Resources (DER), such as flexible loads, controllable generation, or storage resources, to keep the grid stable and to ensure quality of supply. Nevertheless, existing distribution grid energy management mechanisms are not adapted for such evolutions. In order to properly integrate demand side flexibility distribution grids need new energy management architectures, capable of fostering coordination and collaboration among wholesale market actors, DSOs and prosumers[5].

2.2 Demand Side Management and Demand Response

Demand Side Management is a very wide concept that involves programs focusing on three different type of issues: efficiency issues related to the isolation of homes or the efficiency of appliances, social and anthropological issues related to the change in human behavior, e.g. how to gain customer active participation and commitment through personalized feedback, and finally the most advanced level involves the introduction of information, communication and control technologies to have a fine grained management of the demand side. In this last level of management we find DR programs. Demand Response is one of the main applications in a Smart Grid environment, and is about shaping the demand of electricity during certain periods of time (particularly during peak hours) by leveraging the flexibility at customer premises in exchange of some kind of incentive. The flexibility at customer premises is based on the characteristics of elastic loads, modifying their load curves at the cost of an impact in the user experience, and on the use of distributed generation and/or storage facilities, including EV.

DSM programs allow a more efficient use of the available resources, reducing CO2 emissions and operational costs. Particularly, DR programs can improve reliability of the grid helping to fit the demand to the available/planned capacity and enable deferring capital investments by delaying the need for new peak generation facilities and further changes in the grid infrastructure. DR could provide several services at different time scales, ranging from the hour-ahead market, to the tertiary reserve, passing through the fast response reserve, but the market structure must provide incentives for aggregators/utilities to develop DR programs. This is why the roles of markets and regulation are key to understand how a realistic DR system could work. Besides characterizing the possible sources of revenue, markets and regulations define the exchanged products, imposing constrains in how those products are measured and translated into a customer environment, e.g.: regarding time issues, if customers' flexibility will be used only in peak times or all along the day, meaning, if the product in the user side will be to follow a daily curb, to reduce the load during peak time, or both.

2.3 Thesis objectives

As it was described above, present electricity distribution grids were not designed for facing massive deployment of RES on residential premises, nor for the structural changes in load induced by the expected fast growth of the electric car market.

[3]The electricity grid is structured hierarchically into transmission grid level carrying electricity at high voltages across long distances and distribution grids that deliver medium/low voltage electricity in shorter distances.

[4]Flexibility, in this context, can be defined as the capability to adapt demand and/or injection flows of electricity to the grid by adapting consumption patterns, controlling generation output or storing energy.

[5]Prosumers represent the evolution of passive consumer role into a pro-active participation on grid activities.

Two key consequences are, that the opportunities rose by local RES as a major component of the energy transition cannot be fully leveraged, and that, with no architectural paradigm changes towards exploiting demand side flexibility[6], the required investments on infrastructure reinforcement may be extremely high [47].

There is a need for an end to end architecture that, whenever necessary and convenient for players, can integrate the control of edge devices including customer appliances. The IoT paradigm promises to enable connected devices to identify themselves, describe their capabilities, discover each other, and self-organize in order to provide innovative services. In particular, in the context of Smart homes and Smart grids, it will enable customers to seamlessly play a more active role, fostering the provision of flexibility to the grid.

Such flexibility is already being exploited at wholesale electricity markets through recently adopted market mechanisms and new roles. Flexibility is aggregated into Virtual Power Plants (VPP) by Aggregators and offered in substitution of expensive and polluting power plants at the energy markets. Balancing Responsible Entities (such as electricity suppliers) can also use demand side flexibility and transact blocks of energy among them to optimize their participation on the market. The TSO also leverages flexibility for balancing the grid in real time through the Balancing Mechanism (or tertiary reserve).

While wholesale markets and the TSO have adapted to leverage demand side flexibility, DSOs continue reinforcing the infrastructure as the main lever to cope with distribution grid challenges, which is currently hindering RES deployment pace. The use of flexible DER will enable to reduce/defer infrastructure investments and to gain fine grained control over infrastructure and services. But, at present, storage resources and Building Energy Management Systems follow a stand-lone approach, focusing on auto-consumption and local energy efficiency, and therefore may worsen the negative impacts on the distribution grid because of the lack of coordination among actors.

The general objective of this thesis is to design an architecture, based on IoT technology, for providing innovative Residential DSM services, with a special focus on services enabled by self-consumption at the household and neighborhood level. The general objective can be divided in two parts. First, the thesis must provide the architecture building blocks for new distribution grid Energy Management System (EMS), capable of fostering the coordination among actors. It must include recommendations on the means to implement the novel building blocks proposed for this architecture. In particular, such implementation requires to solve issues at the household level of the architecture, related to conflicting transactions that may hinder the control of flexible DER. Such conflicts arrive when controllers from different domains (energy, health, security, comfort) share the same environmental scope or control simultaneously the same edge devices. The second objective has to do with the applications enabled by the architecture, in particular, it should allow DSOs to better control the power balance and quality of supply of the distribution grid. We focus on locally balancing distributed RES production with demand flexibility, which has the potential to alleviate congestion, reduce losses and consequently augment variable RES hosting capacity without further infrastructure reinforcements/extensions.

3 Thesis overview

This work starts by identifying the building blocks of a general architecture for providing residential energy services, based on a comprehensive state of the art of existing IoT technologies with a special focus on interoperability issues. We then suggest improvements to the architecture, addressing the orchestration of controllers for avoiding conflicts and the implementation of Event-Condition-Action (ECA) rules on-premises, to improve security, privacy and service availability. Then we extend

[6] Ability to modify the electricity demand/supply profile

the architecture for tackling energy management issues at the distribution grid level. We propose a novel paradigm for distribution grid management based on the virtualization of the infrastructure into multiple *Virtual Distribution Grids* (VDG), to cope with heterogeneity of resources and actors, and with the inherent complexity of related resource allocation problems. We then focus on a residential VDG, by proposing a multi agent architecture capable of providing demand side management services through the autonomous exchange of transactions among households, service providers and operators. The proposed architecture relies on blockchain technology and self-enforcing smart contracts, as they enable several competing parties to agree on the evolution of the state of a common/shared/-mutualized infrastructure thanks to the security provided by cryptoeconomics[7] and the transparency and auditability enabled by a shared ledger.

With respect to the services enabled by the architecture, we focus on a market application, where households can trade energy with their neighbors an hour ahead of time, aimed to locally balancing renewable energy production. We propose an auction mechanism in charge of the efficient matching of households offers to buy and sell renewable energy. We exploit dynamic transport fee rebates for creating incentives for households to adapt their demand of electricity to the availability of local renewable energy production, in a way that responds to both prosumer and operator needs. In addition, we propose to combine local markets with a dynamic phase allocation mechanism to further improve the quality of electricity supply.

As the rest of models that rely on ex-ante agreements (day-ahead, hour-ahead, etc.) the market requires agents to subscribe a commitment for future energy flows. Nevertheless, energy flows cannot be forecasted with high precision due to their dependency on human behavior and on exogenous variables controlled by nature (temperature, sunshine and wind). Thus, a real-time control of energy resources must be put in place to enforce the committed flows. We propose a near-real time mechanism that provides the means for the distribution system operator to drive households towards a final exchange with the grid that both optimizes individual household goals (favoring the enforcement of the flows agreed on the hour ahead market) and responds to the coupling constraints set by the operator.

The architecture and demand side management mechanisms proposed in this thesis have the potential to alleviate congestion, reduce losses and consequently augment distribution grid capacity for hosting renewable energy sources. We evaluate such potential through comprehensive simulations using power flow analysis and realistic load profiles, providing valuable insight for the design of future distribution grid energy management systems.

4 Summary of thesis main contributions and outline

Following the general objectives of the thesis, the manuscript is divided in two parts. First, the thesis provides the architecture building blocks for new distribution grid EMS, capable of fostering the coordination among actors for the development of innovative residential DSM services. The second, which holds the main contributions of the thesis, proposes three novel applications enabled by the architecture and analyzes their impact on the capacity of distribution grids for hosting renewable energies while maintaining the quality of electricity supply. We propose the exchange of energy among households through markets aimed to locally balancing renewable energy production with residential demand flexibility. Then we propose to combine local markets with Solid-state Transfer Switches for the dynamic allocation of households to phases, which extends the benefits of local markets to a better balance of flows across phases. Finally we propose a real time distribution grid reserve mechanism to drive households towards a final exchange with the grid that responds to the goals of both prosumers and DSO.

[7] The combination of cryptographic technology with incentives and game theory in order to build distributed systems.

The outline of the thesis is as follows:

- **In Chapter 2**, we present the building blocks of a general IoT-based architecture for providing energy services at the residential domain. The architecture is based on an extensive overview of the protocols and technologies supporting the IoT based smart home. The proposed architecture addresses some of the main challenges faced by IoT solutions, with a special focus on interoperability issues, by leveraging existing technologies with a distributed approach in terms of data and intelligence. Finally, we address the lack of orchestration among controllers and we pose the main principles for the implementation of ECA based control entirely on-premises, based on the common abstraction provided by transactions orchestrated by a distributed blockchain-based platform.

- **In Chapter 3**, we first address the main design objectives and requirements of new generation distribution grid EMS and analyze current approaches for coordinating the allocation of flexible DER: Microgrids and VPP. Then we propose the concept of *Virtualized Distribution Grid* as a new paradigm facilitating distribution grid management. We focus on a residential VDG. We propose a hierarchical agent-based architecture capable of providing DSM services through market-based resource allocation mechanisms. We envision the deployment of several markets over a distributed transactive platform to enable households to transact their surplus or lack of energy and the demand flexibility budget with neighbors, utilities, aggregators and DSOs. We propose an innovative implementation for such transactive platforms based on blockchain technology, which provides increased security, transparency and auditability, and the possibility of mutualizing the platform among service providers and infrastructure operators from different domains.

- **In Chapter 4**, we propose the transaction of energy among households through a market aimed to locally balancing the excess of renewable energy production with flexible demand. We propose an auction mechanism and simple transport fee rebates to incentive houses to locally control their flexible demand in a way that benefits both prosumers and DSO. To the best of our knowledge, our work is the first to propose a thorough assessment of the impact of such markets on distribution grid quality of supply.

- **In Chapter 5**, we address the impact of scheduling mechanisms on network unbalance. We propose dynamic phase switching as a mechanism to cope with these issues by coordinating phase switching decisions with market decisions. The mechanisms are simple, they rely only on the information obtained from market decisions about the flows exchanged among households. We provide a thorough assessment of the performance of dynamic phase switching mechanisms.

- **In Chapter 6**, we address the control of electricity flows on a residential low voltage distribution grid in real time. We propose a game theory model that enables households to decide which electricity flows to exchange with the distribution grid in order to minimize their costs. Such costs depend on their individual strategy and also on a penalty signal associated to a coupling constraint on the average strategy of households. This establishes a game that enables households to optimize their own costs while reducing voltage rises/drops and current flows on the lines.

Part II

Novel architecture for distribution grid energy management

Chapter 2

Smart Home IoT-based architecture

The Internet of Things (IoT) paradigm has been pushing a new wave of Smart Home connected devices and related services, for which the energy domain represents one of the main business cases, due to the need to exploit the flexibility potential of household devices that consume, store or produce electricity. In this Chapter we present the building blocks of a general IoT-based architecture for providing energy services at the residential domain. The proposed architecture addresses some of the main challenges faced by IoT solutions, with a special focus on interoperability issues, by leveraging existing technologies with a distributed approach in terms of data and intelligence.

1 Introduction

The deployment of distributed Renewable Energy Sources (RES), Electric Vehicles (EV) promotion and energy demand curb shaping are key means to fulfill the energy transition goals. However, the electricity grid was not designed to cope with the load dynamics imposed by EVs, neither to deal with the increasing weight of RES in the energy mix. As generation becomes less predictable and controllable, energy operators will be forced to adapt their energy management strategies to keep the grid stable; for which Demand Side Management (DSM) mechanisms and particularly Demand Response (DR) will become major levers.

This new paradigm will require a change in consumers' role from a simple subscriber to a main grid actor, involved in energy production, storage, consumption shifting and trading; but not even the most committed consumer will be able to sustain such an active role. Therefore, advanced communication and control technologies will need to be applied to ease participation and to enforce customer policies. In particular, IoT technologies are the main foundation over which a control plane can be built to allow the implementation of advanced household energy services.

Despite the Smart Home being an old concept with limited success, related products and services have been receiving a lot of attention in the last 5 years, with IoT being the main enabler for such increased interest. Nevertheless, the Smart Home has been one of the slowest areas of adoption of IoT technology [48], which has been embraced mainly by early adopters. This is mainly due to a lack of customer perceived value with respect to costs, security and privacy concerns [49]. Lack of interoperability is hindering innovation and customer value creation, while imposing complexity to users and developers. Security and privacy have been treated as an afterthought [50], which leads to privacy concerns, insufficient authentication and authorization, lack of encryption, among other security issues, even on the most popular IoT devices [51].

In this chapter we propose the functional and technological building blocks for implementing a general IoT-based architecture for providing residential DSM mechanisms and related energy services. The proposed architecture addresses some of the main challenges faced by IoT solutions, with a special focus on interoperability issues, by leveraging existing technologies with a distributed approach in terms of data and intelligence, enabling the extension of cloud[1] capabilities to the edge. In order to structure our approach to build a general end to end architecture, we consider three architectural layers: functional, physical and communications. The functional architecture aims to identify and synthesize the means by which smart home services provide value to users, the components architecture describes the technologies that enable the deployment of such functionalities on the field, and the communications architecture addresses the protocols supporting the interactions among devices and between devices and users.

2 Functional Architecture

In an IoT-based architecture there are three fundamental functional groups. The first group is the set of functions at the edge of the architecture, enabling the merge between the physical and digital world. These *Edge Functions* (EF) can be divided into sensing the environment (context awareness), acting on the environment (state management) and user interaction. The second group represents functions related to data management and treatment, based on which applications execute business logic to provide customer value. We refer to this group as *Cloud Functions* (CF), as for most of current IoT products and services such functions are implemented over cloud infrastructure. The last functional group is called *Networking Gateway Functions* (NGF) and is in charge of enabling the interconnection among EF and CF function groups, by providing the functions related to connectivity, interoperability, device & resource discovery, securing communications (e.g.: secure pairing and onboarding), etc.

These functional groups can be implemented in many different ways, at different levels of the architecture. The best implementation depends on the applications for which the architecture will be applied, so an important quality of a general architecture is to enable flexible and heterogeneous implementations of such functions. In the next sections we analyze the technology options for implementing the functional architecture into physical components and to enable the communication among them.

3 Physical Architecture

3.1 Implementation of *Edge Functions*

The set of relevant abstract objects implementing EF are Sensors, Beacons and Radio Frequency Identification (RFID) tags providing context awareness, Actuators enabling device state management, and User Interaction (UI) objects. These object types are generally implemented as battery-powered devices or using energy harvesting techniques to avoid the costs and burden of battery substitution[2].

Energy harvesting devices are based on extremely constrained hardware capabilities, specifically designed for harvesting characteristics and code is run directly on firmware. The abstract objects that can be implemented using energy harvesting technologies are mostly passive Tags, Sensors and

[1] For cloud we understand the virtualization of physical infrastructures and their decoupling with respect to geographical location. The cloud represents distributed storage and processing capabilities that can be implemented at different levels of the architecture.

[2] This is not the case for complex UI objects, such as big screens, but here we focus on simple UI implementations.

simple UI (Piezoelectric wireless switches, solar-powered thermostats, etc.). The main technologies providing energy harvesting capabilities to edge devices are EnOcean and RFID.

Battery powered devices are preferred when application requirements are not adapted to energy harvesting constraints or for objects such as actuators or beacons. In terms of hardware, there are several development platforms for prototyping, such as Arduino, Zolertia, OpenMote or ARM's mbed, which are based on microcontrollers (e.g.: ATmega328), small processors (e.g.: ARM Cortex-M0, M0+ or M3)[3] or a System on Chip (like the Texas Instruments CC2538 which costs less than $5 in quantity), including an embedded processor and a radio transceiver. With respect to Operating Systems (OS) adapted to constrained devices, there exist several lightweight OS such as Contiki, TinyOS and RIOT, from which RIOT has superior characteristics, such as real time behavior, advanced communication stack (full Internet Protocol version 6 (IPv6) and CCNlite support) and C and C++ programmability [1]. Brillo, the Android-based OS recently announced by Google also supports battery powered devices, but would require storage and RAM resources in the order of MB while current platforms for edge devices provide only tenths of KB of RAM and hundreds of KB of flash memory.

3.2 Implementation of *Cloud Functions*

In current implementations of Smart Home Services, most of the data and the intelligence are concentrated at the back-end. However, some amount of data processing could be distributed towards the edge to better enforce customer privacy policies, to avoid delays in applications requiring real-time response and to improve availability by enabling CF on offline mode. The implementation of the back-end system being out of the scope of this work, we focus on Personal Clouds and Smart Objects, which represent CF implemented at customer premises. We could think of Smart Objects as implementing what we call *emotional intelligence*, which enables a device to detect an event, recognize the context and take the appropriate action, as following an Event-Condition-Action rule. On the other hand, Personal Clouds would implement *cognitive intelligence*, implying more complex functions such as forecasting, optimization and learning mechanisms.

Personal Clouds rely on powerful processors, such as Freescale's i.MX6 Quad processor, enough flash and RAM to support a full OS and several applications, and a SATA interface for connecting a hard disk. Wandboard Quad and the CuBox-i 4x4 are two possible platforms with the described characteristics. In addition to full fledged OSs, there are alternative lightweight Linux server platforms, better adapted to IoT environments[4]; from which CoreOS is the most adequate for a Personal cloud, as it has been focused on the server side while Snappy Ubuntu Core is better adapted to Smart Objects or Gateways. Such platforms substantially improve security and flexibility, by leveraging container management tools, such as Docker or Rocket, providing isolation among applications and a better management of updates (difference-based or transactional upgrade/rollback).

Smart Objects require less hardware capabilities than Personal Clouds, and thus are implemented as applications on personal mobile devices, or on mains-fed devices for applications that need to be continuously available. BeagleBone Black (BBB) is one of the best adapted development platform for such mains-powered devices, for its processing capabilities, modularity/flexibility and stronger reliability. In addition to the mobile OSs that may be used for such devices, Snappy Ubuntu Core is a good alternative, as it is supported by BBB and can be easily integrated with cloud platforms based on Ubuntu OpenStack. Google's Brillo could be used as Smart Object OS, especially when hardware capabilities are somewhere between a BBB and edge device platforms such as OpenMote, and all the features provided by a mobile OS such as Android are not necessary.

[3] Note that the new Cortex-M processor family based on the ARMv8-M architecture will bring support of TrustZone security technology for the smallest processors. See www.arm.com/products/processors/technologies/trustzone.

[4] https://blog.docker.com/2015/02/the-new-minimalist-operating-systems/

3.3 Implementation of *Networking Gateway Functions*

There are three implementation possibilities for interconnecting CF and EF implementations into cloud infrastructure, edge devices and physical gateways:

- Edge devices connect to cloud infrastructure through cellular networks, by including a SIM card on each device.
- Edge devices connect to cloud infrastructure through long range & low bitrate technologies, such as LoRa (Long Range) or SigFox (Ultra Narrow Band).
- Edge devices connect to cloud infrastructure through short range technologies, with a local equipment implementing the endpoint for Physical and MAC layers.

The first two options require the implementation of CF and NGF at the cloud infrastructure or on the access network; what deters the possibility of distributing the implementation of CF by extending cloud infrastructure capabilities to the edge. Furthermore, the characteristics and requirements of cellular networks and long range & low bitrate technologies, such as costs, bitrate, energy consumption and maintenance may not be adapted to constraints from Smart Home Services. Thus, the local deployment of a physical endpoint, implementing most of NGF, would be necessary to optimize the distribution of data and intelligence for avoiding delay, reliability and privacy issues.

The requirements for the implementation of the Physical Gateway device are centered on native support for the relevant protocol stacks, reliability and security features. Currently there are some IoT gateway development platforms, such as OpenPi, OpenKontrol Gateway, or even the BBB can be used with connectivity extensions, priced around $40, which highlight the low cost of building a gateway device. The implementation of a custom designed Gateway device can leverage the AM335x ARM Cortex-A8 used by the BBB, as it is cheaper (sells for $5 in quantity) and simpler (development, power management, etc.) compared to the popular Cortex-A9 multi-core platform. With respect to OSs and according to the requirements we would consider mbed OS as the main choice thanks to is broad support for connectivity technologies. In the case of Snappy, the OS has the flexibility to adapt to different technologies, but drivers are yet to be developed.

4 Communication Architecture

The communication architecture consist of the protocol stacks that power interfaces among functional blocks, i.e.: among particular devices implementing such functions. EF implemented by constrained devices represent the essence of any IoT implementation and are the source of most significant challenges due to their limited capabilities. Thus, we focus on interfaces with energy harvesting and battery powered devices, which need to be implemented by the physical gateway device. Additionally we analyze the interface with the back-end. Finally, we address interoperability issues and current technology proposals to enable communications among heterogeneous function implementations.

4.1 Interface with energy harvesting devices

In order to enable “unlimited” autonomy, the communication technology for devices powered by energy harvesting techniques needs to be adapted to the constrained characteristics of the specific harvesting process, which enables communications (push information) only when enough energy is provided. RFID, Near Field Communication (NFC) (RFID-based) or EnOcean are most known and widely used communication protocols running over pure energy harvesting devices[5]. RFID passive

[5] ZigBee Green technology is also capable of handling energy harvesting devices, but as an adaptation of an existing protocol instead of a solution from scratch.

Tags are designed to harvest energy from RF signals and to backscatter the energy carrying tag's data towards the reader. Thus, RFID tags are used mostly to communicate metadata about a device or a location, while NFC is used also for exchanging authentication information enabled by very short range and bidirectional flows. EnOcean can be used for UI devices as well as for alerting and local control loops for automating simple tasks. These technologies define a complete specification from the physical layer to the Application Profiles, defining syntax (NFC Data Exchange Format) and semantics (EnOcean Equipment/Generic Profiles) of the messages and data exchanged. Due to the specifics of such technologies, a gateway is needed to inter-operate with Internet Protocol (IP)-capable devices.

4.2 Interface With Battery-powered Devices

As a consequence of the share of energy consumed by RF transceivers, battery-powered devices need to function in very low duty cycles (sub-1 percent) and communication protocols need to adapt to sleeping periods where devices are not available. This highlights the importance of considering communication protocols optimized for efficiency and to limit communication overhead. We analyze at different layers which are the relevant protocols for interacting with this kind of devices.

4.2.1 Link & Network Layer Technologies

Bluetooth Smart/Low Energy - Bluetooth Low Energy (BLE) is one of the most relevant protocols for IoT-based Smart Home Services, mainly due to its consolidated presence in personal devices, which reflects its maturity and widespread ecosystem. It also provides advantages such as low cost, low energy consumption, flexible application framework (GATT profiles) and Service Discovery Protocol. Furthermore, some of the negative characteristics of BLE, such as non-IP compliance, were addressed by Bluetooth 4.2 specification including IPv6/IPv6 over Low power Wireless Personal Area Networks (6LowPAN) compatibility and further improvements in terms of security, privacy and data rate. In spite of not being addressed by version 4.2, Bluetooth Special Interest Group has recently released the new version of BLE, Bluetooth 5.0, that includes mesh capabilities, which would solve low range issues and also the limitation on the number of nodes that can be active at the same time (7 peripheral devices connected to a central node). In addition, BLE provides further context awareness (mainly location or proximity) thanks to beacon functionality, for which main implementations are iBeacon for iOS devices and AltBeacon as an open specification. In spite of the few limitations signaled, BLE is the best suited protocol for resource constrained devices to communicate under short range with personal devices, for providing gateway functionality, direct control of devices, or context awareness.

The networking IoT stack - The standardization of the networking IoT stack, formed by the 802.15.4 PHY & MAC IEEE standards and 6LowPAN and RPL IETF specifications [52], designed to have reliable IP communications over a constrained network of objects, has been one of the major drivers for the evolution of the IoT paradigm. The IEEE 802.15.4 standard specifies the physical and MAC layers for low consumption and low data rate Wireless Personal Area Networks. 6LowPAN was developed to enable IPv6 communication over 802.15.4 links using an adaptation layer (later extended to other link-layer protocols, e.g.: Power-Line Communications). 6LowPAN provides IP and User Datagram Protocol (UDP) heather compression functionality, packet fragmentation and reassembly, and an adaptation of the IPv6 Neighbor Discovery. 6LowPAN also enables mesh networking over 802.15.4, providing reliability and also the possibility to build larger networks. In order to build a layer 3 mesh network the IETF Routing Over Low-power and Lossy networks (ROLL) Working Group created RPL, an IP layer routing protocol that takes into account IoT requirements for several different applications.

Thread - Thread is an IPv6 networking protocol stack built over IEEE 802.15.4 PHY & MAC and based on IETF standards such as 6LowPAN, RIP (RFCs 1058 and 2080), UDP and Datagram Transport Layer Security (DTLS). It is meant to support any low-bandwidth application layer running over IPv6, such as IPSO Smart Objects [2], providing basic services required for such applications (UDP messaging, multicast messaging, etc.). Thread adds a security architecture, which allows users to simply and securely add or remove devices to the network through personal devices or any other UI-reach device on the network. Thread architecture also provides extended flexibility and reliability, based on mechanisms such as: router eligible devices capable of auto-configuration into router devices for reliability issues, automatically self-elected leader for making decisions such as choosing an eligible device to become router, and support for multiple border routers (forward messages over non-thread networks) with failover capabilities.

Thread stands as a game changer with respect to widely deployed protocols such as Z-Wave and ZigBee. While Z-Wave has the best interoperability on the market, it is mainly due to the silicon and software stack being produced by a unique company, which races trust, scalability and sustainability issues. In the case of ZigBee, the lack of interoperability among devices and protocol stacks, most of them non-IP-compatible, is widely known. Furthermore, any device with a 802.15.4 chip can be made Thread compatible with just a software update, and the ZigBee Alliance is already collaborating with Thread Group to enable the ZigBee Cluster Library (most important piece of ZigBee) to run over Thread networks. Taking into account reliability and security improvements with respect to competitors and the market support represented by Thread Group members, we can consider Thread technology as the selected "industrial-level" implementation of the networking IoT stack.

4.2.2 Application Transport Protocols

The most relevant application transport protocol for interfaces involving constrained devices is the Constrained Application Protocol (CoAP), standardized by the IETF CoRE Working Group. CoAP is a clean-slate designed REpresentational State Transfer (RESTful) protocol, running on UDP with DTLS, but with a transparent mapping to Hypertext Transfer Protocol (HTTP) for reaching Internet services through simple proxies. It is a binary protocol with low parsing complexity and small message size, targeting low cost 8-bit microcontrollers with small amounts of Flash and RAM. CoAP has native Request/Response support, which makes it suitable for direct/remote control of devices or for firmware/software upgrades rather than for capturing sensor data. Nevertheless, there is the CoAP Observe mechanism, which enables a client to receive updates on the representation of a resource from the server (e.g.: a sensor) during a period of time. CoAP Observe avoids long polling (HTTP) but still represents very limited publish-subscribe (pub/sub) functionality. Furthermore, there is an IETF Internet-Draft proposing a CoAP pub/sub broker using CoAP Observe features for handling subscriptions to topics[6].

As CoAP is best suited to a state transfer model than to an event based one, protocols specifically designed for pub/sub functionality, and thus enabling asynchronous and loose-coupled communications, can be considered a better choice for collecting data from sensors. Message Queue Telemetry Transport (MQTT) (OASIS standard since 2014) implements a broker-based pub/sub messaging pattern, with simplicity and lightweight being two of its main objectives. It requires a reduced client footprint and is meant to be super-compact on the wire. However, it runs over Transmission Control Protocol (TCP), requiring a continuous connection to the broker, which is not adapted to low duty-cycle battery-powered devices. MQTT-SN (MQTT for sensor networks) is a variant that runs over non-TCP/IP transports (UDP or SMS (Short Message Service)) and relies on 6LowPAN to adapt to constrained MAC/PHY layers. In order to cope with long sleeping periods, an offline keep-alive process is defined through which servers buffer messages that can be recovered by clients once they wake

[6] https://tools.ietf.org/html/draft-koster-core-coap-pubsub-03

up. Although it would provide a solution for MQTT shortcomings for constrained devices, it is not a mature protocol yet and still lack of tools and platforms for developers. For these reasons we think that using CoAP protocol with the observe mechanism is currently the best solution for constrained devices.

4.2.3 Data encoding formats

Text based encodings, such as JavaScript Object Notation (JSON) and eXtensible Markup Language (XML), are human readable and are widely used on the web, what makes them more suitable for developer ease of life, but less efficient for constrained IoT devices (with JSON being more human readable and efficient than XML). The advantages of binary encoding protocols for IoT devices are a smaller message size and that are easier to process for machines than text based ones due to low parsing complexity. Concise Binary Object Representation (CBOR) is one of the most relevant serialization formats for constrained devices, as it was developed for the Internet of Things based on JSON data model; in addition it enables the inclusion of tags for extensibility. There are also compression mechanisms for text based encodings, such as Efficient XML Interchange (EXI), which is a compressed form of XML. It has the advantage of being more efficient on the wire but requires more processing on the end points. The usage of one or other data format will depend on constraints of components and on the functional-specific requirements regarding data exchange.

4.2.4 Application Profiles

There exist two relevant application layer protocols that were specifically developed for energy management applications: Smart Energy Profile (SEP 2.0) and Open Automated Demand Response (OpenADR). Both standards enable open and interoperable message exchange between devices providing/using energy services and utility companies, aggregators and system operators. Nevertheless, SEP 2.0 is more focused on devices inside the home, considering devices such as displays and thermostats that need to implement function sets, e.g.: a Smart Appliance type of device must implement Demand Response/Load Control, Pricing and Base function sets (shared among device types); while OpenADR only specifies the interactions and signals between a Virtual Top Node (Server) and Virtual End Node (client), and thus the intention is to interact with customer energy management systems enabling autonomous reaction to a DR signal.

OpenADR uses Common Information Model (CIM) objects to build the data model. Messages are coded using XML and exchanged through Simple Object Access Protocol (SOAP) or RESTful interfaces over HTTP and extensible Messaging and Presence Protocol (XMPP) transports. SEP 2.0 provides a link layer agnostic RESTful interface based on HTML (HyperText Markup Language), with XML or EXI serialization over TCP/IP and TLS (Transport Layer Security). SEP 2.0 also defines a lightweight HTTP-based pub/sub extension and specifies multicast Domain Name System (DNS) (mDNS) and DNS Service Discovery (DNS-SD) as discovery mechanisms. SEP 2.0 information model is compatible with CIM, simplifying the translation of messages between both standards, which is important due to their overlapping functionalities that may be concealed using SEP 2.0 inside the Home Area Network (HAN) and OpenADR between the HAN and the service provider [53].

The complete set of specifications and technology choices of SEP 2.0 constrain its usage to high-end devices, as its implementation requires at least a cortex M3 with 200 Kb of memory [3]. For this reason and due to the energy domain specificity of the profile it may not gain massive uptake with device makers and service developers. In that sense, a more general application profile, such as IPSO Smart Objects [2], may be better adapted. As a matter of fact, IPSO object model is based on the Lightweight Machine to Machine (M2M) specification from the Open Mobile Alliance for device management. Lightweight M2M is itself based on IETF CoAP, so it provides a simple and flexible object

template specifically adapted to constrained devices. For this reason IPSO Smart Objects is useful on constrained networks and supports advanced IoT protocol features such as asynchronous notification and resource discovery. Furthermore IPSO object model defines several abstractions useful for energy management purposes, such as power or load control, which can be complementary with SEP 2.0.

4.3 Interface with the Back-end

4.3.1 Link & Network Layer Technologies

The lower layers conforming the interface with the back-end are in most cases IP-capable technologies: e.g.: Ethernet over Fiber Optics or xDSL (Digital Subscriber Line), used by Internet Service Providers' boxes, and mobile broadband technology (3G or LTE (Long Term Evolution)) when mobile devices are used as gateways. Other protocols, such as Weightless protocol, LoRa or SigFox, can also be used for Wide Area Network (WAN) communications, particularly for connecting devices without a gateway, or as an out of band/backup connection. These technologies may eventually become an alternative to Internet providers for IoT applications.

4.3.2 Application Transport Mechanisms

In the general case, the most commonly used architecture model for the transport of application data is the RESTful style, for which HTTP is the most common protocol. Other architecture models can be used depending on the application: SOAP can be used for implementing complex business logic, or WebSockets for bidirectional communications requiring data streaming or live data feed. One of the strongest advantages of HTTP is the scalability enabled by simple interfaces with a reduced set of methods (Create, Read, Update, and Delete), easing interoperability across platforms and implementations. In spite of being widely adopted it has some drawbacks, as the lack of native support for pub/sub mechanism, NAT/firewall traversal issues requiring port forwarding or long connections, and lack of multicast capabilities. A version 2 of HTTP is under development and will provide improvements such as header compression, server push and better mobility support. CoAP can be an alternative for HAN/WAN communications thanks to some improvements over HTTP, such as better efficiency for small payloads, multicast support, and the Observe capability.

As we previously stated, pub/sub messaging pattern is better adapted for data collection from sensors than Request/Response mechanisms. For this reason we consider Data Distribution Service (DDS) and MQTT as two relevant pub/sub messaging protocols. MQTT was already introduced as a relevant protocol for constrained devices, but it can also be used for less-constrained devices, e.g.: Facebook uses MQTT as the back-end technology of its Messenger application. Most of MQTT limitations are cited by [54], the most relevant of which are payload obliviousness and lack of discovery mechanisms, hindering interoperability among implementations. DDS, which was standardized by the Object Management Group, can be considered a good alternative to MQTT for providing reliable distributed pub-/sub communications without brokers. It has been widely applied in industrial/enterprise Local Area Network (LAN)/Virtual LAN (VLAN) environments due to characteristics such as strong security, high reliability, flexible Quality of Service (QoS) policies and real-time communications [55]. Some of its limitations for use in WAN environments are addressed on [56], where they propose to use Session Initiation Protocol to overcome limitations such as isolated DDS domains, lack of multicast support and lack of QoS provisioning mechanisms.

As both mechanisms pub/sub and request/response are needed, a single protocol capable of efficiently handling both would be a better option. We consider XMPP as the most relevant messaging protocol for such a task, due to the limitations of other technology alternatives, such as AMQP (Advanced Message Queuing Protocol) [57], ZeroMQ and nanomsg [58]. XMPP was first developed in the context of Jabber open source project targeting the provisioning of communications and presence

for chat applications, then was standardized by the IETF and is currently a widely deployed messaging system. XMPP is one of the most feature rich application transport protocol, enabling multicast communications and push messaging pattern, and can provide strong security and privacy mechanisms. This is possible thanks to its extensible nature for supporting IoT-specific requirements, as for example support for Sensor data, device provisioning and security[7]. Furthermore, XMPP has been the protocol of choice for several relevant technologies, such as OpenADR, IEC 61850 and AllJoyn, which we introduce later.

4.3.3 Data encoding formats

As we previously stated JSON and XML are the most used data serialization formats of the web, with JSON being more developer friendly, efficient and with less overhead. Furthermore, JSON Linked Data (JSON-LD) provides the possibility of extending JSON by adding metadata tags, rendering resources machine-readable, allowing applications to follow embedded links leading to further resources.

4.4 Interoperability Considerations

The lack of interoperability among components and function implementations is hindering innovation and further customer value creation. This is in part a consequence of heterogeneity and complexity as we highlight by considering the implementation of device and service discovery mechanisms. Such basic connectivity functions are traversal to all components and interfaces of an architecture, but their implementation is strongly dependent on the protocols involved. Discovery mechanisms are strongly coupled to underlying protocols: Bluetooth Service Discovery Protocol is used for BLE bindings, the discovery protocol for constrained devices using CoAP is based on CoRE Link Format, and, for non-constrained IP environments, Zeroconf mechanism (based on mDNS and DNS-SD) is widely deployed. Thus, a layer of abstraction would be needed, capable of leveraging available discovery mechanisms while providing a unified interface for applications and users. In more general terms, the challenge is to provide open and interoperable ecosystems for application development, data exchange and resource sharing in order to foster the development of services focused in adding value to customers and improving their experience.

4.4.1 Interoperability building blocks

In order to enable the exchange of messages between two devices, they need at least to share the same PHY/MAC, Network, transport layer and encoding protocols. In the lack of such a common stack, a gateway device (or a network of devices) would be needed, capable of communicating using the two different protocol stacks and providing a common interoperable layer. Similarly to the thin waist of the hourglass model that allowed Internet explosive growth, the IP protocol can be considered as the main layer over which the different link layer technologies at the home will be made interoperable. But relying only on IP is not enough for interoperability, as different devices can still use different data encoding and transport mechanisms, i.e.: JSON/HTTP/TCP, CBOR/CoAP/UDP, EXI/XMPP/TCP, etc.

In addition of sharing a common protocol stack, devices or entities that provide services, need to publish an interface description through an Application Programming Interface (API), including available operations, corresponding inputs and outputs, data structure and types, etc. Interoperability at the application level can be gained through such APIs, enabling service mashups, which are generally established between two entities (“Cloud to cloud mashups”) and need to be specifically established for each case [59]. The problem comes from the heterogeneity of APIs in terms of structure and data models. Most Web APIs are implemented with the same set of protocols, but each API is

[7] http://wiki.xmpp.org/web/InternetOfThings

organized differently. Thus, developers need to learn the organization of every API and write adapted code for each service their application needs to interface with. To make such interoperability scalable and reduce complexity for developers there are two approaches: a reduced set of common APIs or a shared specification for constructing and organizing APIs, as part of a framework or an adaptation layer. Any party implementing an interface following framework recommendations or using common APIs would be able to interact with the others and share data and resources.

Finally, in spite of entities being able to share data and resources, a common understanding of data in terms of semantics is still needed. Information/Object Models are a fundamental interoperability building block, as they enable the representation physical entities in the digital world, by abstracting their properties, their status and their functions. In order to have real interoperability, participating entities need to agree on common data models or application profiles, to understand the meaning of the data being exchanged.

4.4.2 Classifying Interoperability Approaches

In this section we analyze current technology approaches for the creation of interoperable ecosystems, by characterizing them according to the distribution of intelligence and data they enable: at the back-end, at the gateway level and among devices in a distributed fashion. All three possibilities are valid and may need to be combined for providing an end to end architecture for smart home services.

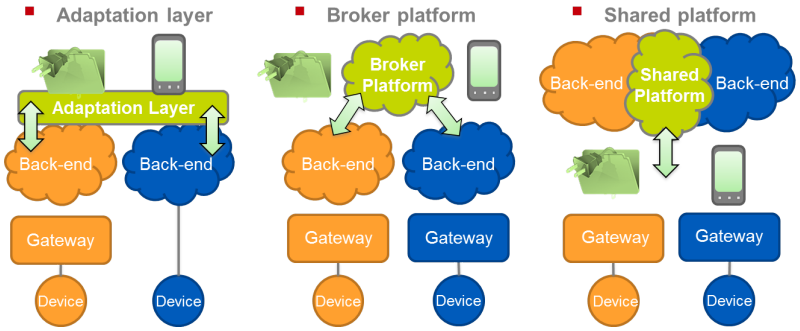


Figure 2.1 – Back-end Interoperability

Back-end Interoperability - Reliance of current connected products and services on back-end data storage and processing capabilities has pushed interoperability towards the core of the architecture, based mainly on the exposure of web APIs over common web protocols (OAuth 2.0, HTTP, JSON, TCP/IP), for communications between data hubs and with edge devices. Dumb gateways are deployed for enabling edge devices to interact with the back-end, by doing HAN to WAN protocol translation and using APIs to upload/receive data. As a consequence, devices are not interoperating with each other, but the Information Systems at the core of the silos share data to provide new services to the user.

We can differentiate three types of approaches towards back-end interoperability (Figure 2.1). The first type is based on a distributed adaptation layer, based on standardized APIs or based on a framework providing common API structure and common semantics. An example of such approach is HyperCat framework. The approach of HyperCat is based on a common machine-readable and searchable organization of APIs, including a structured description of resources in a RDF-like (Resource Description Framework) form. Though, it has the drawback that still requires the agreement

among parties on common semantics for metadata tagging. The second type leverages a broker platform, in charge of the hard work of translating heterogeneous APIs and data models exposed by "client" platforms, into a common set of APIs. IFTTT (If This Then That), Wink and Temboo are relevant examples of such broker platforms. The third approach is a shared platform, which is a sort of merge of clouds into one common infrastructure. It provides a unique interface, including the APIs description and an object model to have access to a shared data repository and/or to analytic capabilities for the treatment of stored data. The shared platform does not need to handle complexity and heterogeneity, because all the interactions are carried through the imposed interface. Works With Nest, Google Fit, ThingWorks and OneM2M are examples of such a shared platform, with OneM2M being a special case as it is a standardized platform that can be hosted/implemented by several actors.

These platforms are focused on abstracting complexity for developers and/or consumers and creating interoperable ecosystems. Complexity is abstracted from developers by providing a reduced set of stable APIs and from consumers by enabling the access to heterogeneous services and device capabilities through a unique interface/application. When data repository and common semantics are provided by the platform, interoperability and data sharing are further eased compared to only providing a common API organization. With respect to privacy, the centralization of data and its treatment on the cloud pose challenges regarding the enforcement of privacy policies, particularly in terms of usage control, while in terms of security, current state of the art web technologies for authentication and encryption can be leveraged.

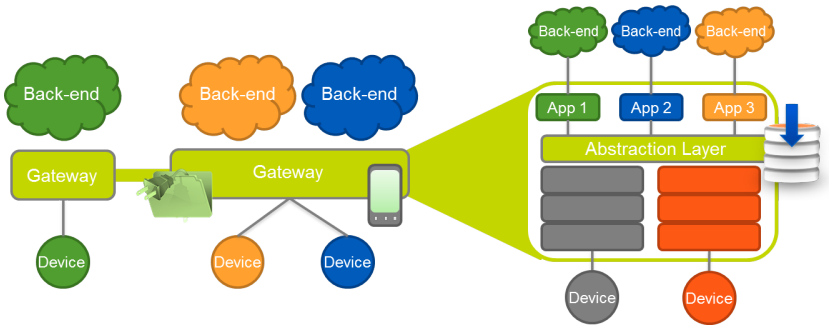


Figure 2.2 – Interoperable gateway

Interoperable Gateways - The particularity of interoperability at the gateway level is the heterogeneity of communication protocols requiring an abstraction layer (Figure 2.2). Based on a shared data model such layer provides a common set of APIs for decoupling applications and device implementations, allowing applications from any service provider to interact with any device regardless of device implementation characteristics. The distribution of data and intelligence is improved by making it possible to distribute application logic between the back-end and the gateway. This would reduce infrastructure costs and potentially improve security and privacy enforcement, by reducing attack surface and mitigating consequences of an attack [4]. IoTSyS is an example of an interoperable gateway issued from the academy, and the collaboration among EEBus, Agora and Energy@Home is a relevant example of an industrial project with a focus in energy. In the case of mobile devices the abstraction layer strategy implies moving a step beyond the App store model, allowing applications from different manufacturers to share data. The best examples of such a framework are Apple's APIs called HomeKit and HealthKit. Such APIs represent a strong signal regarding the extension of cloud capabilities to the edge and the rising importance of people's trust, particularly regarding sensitive data, which is kept on the mobile together with the encryption keys for when data is backed-up on

iCloud. The main issue of these frameworks is that are tied to Apple user interaction devices and have high barriers to entry for third party accessories. In addition, HomeKit does no allow applications to interact with the database while in the background, deterring automation by focusing only on their major strength which is voice interaction through Siri.

Distributed Interoperability Across Devices - Finally, device level interoperability further enhances distribution of intelligence allowing any application to interact with any other application running on any other device (Figure 2.3). Thus, any device with enough capabilities would become an interoperable gateway for other constrained devices, enabling distributed implementations of most NGF, e.g.: securely onboarding a device into the WiFi network using UI capabilities and credentials from another device. Such peer-to-peer interoperability can be obtained thanks to a middleware layer, allowing device-to-device communication in a platform and transport agnostic fashion. The downside of such a distributed ecosystem is that requires complex orchestration of transactions among devices to enforce customer policies and to avoid conflicts among applications following different customer goals.

The main example of this type of interoperability is provided by AllJoyn, a platform-neutral application development framework designed to simplify proximity networking across heterogeneous devices and distributed applications. It provides a radio-link agnostic transport mechanism based on an extension of the Linux D-Bus specification (Data type system, marshalling format, naming guidelines, over-the-wire protocol, etc.), supporting protocols such as WiFi, WiFi Direct, Power Line Communication (PLC), Ethernet, BLE. As well as cloud-based platforms and interoperable gateways, it provides basic functions such as device/service discovery, connection management and security enforcement. The main contender technology is IoTivity from Open Interconnect Consortium (OIC), which is based on CoAP and Samsung Smart Home Data Model. The technology is still under development but the consortium has already signed collaborations with IPSO alliance, Industrial Internet Consortium and EEBus, thanks to their web of things like approach. In addition, OIC acquired Universal Plug and Play (UPnP) Forum assets, which had been promoting UPnP+ and UPnP Cloud as adaptations of UPnP standards to IoT and Cloud paradigms.

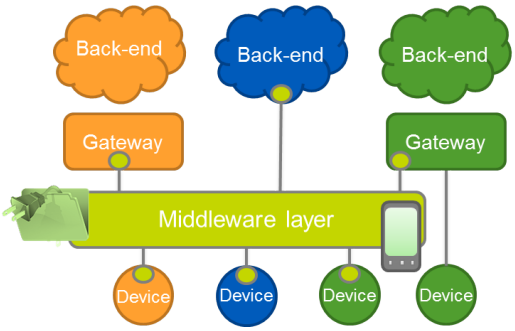


Figure 2.3 – Distributed Interoperability Across Devices

5 General Architecture Improvements

Smart Home services have been historically provided through siloed architectures which have made interoperability among devices and services from different domains a challenging endeavor. The Internet of Things paradigm has appeared with a promise of innovative services, extracting value from

novel interactions among users, devices and their environment. Nevertheless, the IoT driven Smart Home has barely started to show its potential. This section addresses three of the main issues that hinder the development of IoT services in the context of Smart Homes: The interoperability issues among devices from different manufacturers providing services on various domains, the orchestration of such services for providing a coherent smart home behavior, and the sustainability of business models supporting the IoT based Smart Home.

The motivation for this section comes from the change on the role of consumers towards an active participation on Demand Response programs, which involve commitments from households on the energy/power to be exchanged with the grid during certain periods of time. The specific challenge for the energy domain is to autonomously enforce such commitments in a Smart Home context where there are several devices from different manufacturers providing services that satisfy user needs from various domains other than energy. This means that such devices need to achieve an agreement on the evolution of the state of physical resources (Physical world) and of the information representing those resources and their environment (Digital counterpart of the physical world). In this Section, assuming interoperability issues are solved and that devices from different manufacturers are able to interoperate, we address the second major issue which is that of the orchestration of devices, proposing an architecture based on blockchain technology (distributed ledger) to achieve a coherent smart home behavior. Furthermore, we discuss the conditions under which the solution would be profitable for all the actors (users, service providers and edge devices providers).

The system under study can be represented by three types of agents: users, controllers and edge devices. The role of users is to fix the policies and to validate the desired behavior of smart devices and corresponding services under different contexts; additionally they interact with devices through their UI capabilities or through the environment. Edge devices are sensors and actuators that enable to capture and transmit data/information about the environment or to act on the environment based on received data/information/commands. Controllers are the smart devices that represent services by locally processing data/information/commands or by being the point of presence of the service when at least part of the processing is realized outside the household, as it is generally done by cloud services when external resources or data need to be aggregated or when there is some heavy processing such as data mining/machine learning is needed.

5.1 Orchestration of transactions across multi-service controllers

Having reviewed the IoT interoperability issue and the existing technologies that are paving the way towards its solution, we now address the challenge of device orchestration, which is to obtain a coherent behavior respecting customer policies from the interaction of objects from different manufacturers providing services over different domains of expertise.

Following the trend for distribution of intelligence towards the edge, we can imagine there will be several dedicated controllers for providing services on domains such as health, security, entertainment, etc. The decision processes of those controllers influence the environment through control transactions sent to actuators. Such processes pursue different objectives but may share the same set of actuators or the same environmental scope. The lack of orchestration among controllers will lead to conflicts that can undermine interoperability and increase complexity of Smart Home Services [5].

5.1.1 A distributed transactive approach

Issues with conflicting digital transactions are generally solved by putting trust in a single entity in charge of centralizing control, keeping a global ledger of the state of devices and clearing transactions for avoiding conflicts. An example of such an entity is *Works With Nest* platform, which maintains a centralized document with the state of all resources involved. The document is synchronized among

partner entities and allows to implement simple ECA-like rules for controlling the behavior of connected devices, e.g.: while approaching home on the connected car, the document is modified and synchronized, and a simple rule is triggered for the thermostat to start heating in advance.

Simultaneously, *Works With Nest* enable households to participate to rebates proposed by utilities in exchange for reducing electricity consumption. The platform orchestrates thermostats to avoid conflicts between pre-determined rules and the enforcement of commitments with utilities.

Distributed middlewares like IoTivity or Alljoyn do not provide a mechanism to solve conflicts, but offer devices the possibility to fulfill orchestrator role as a service. Taking advantage of the open and interoperable nature of IoTivity/Alljoyn, such a centralized orchestrator wont favor siloed ecosystems, but will require access to every edge device and to gather all the information needed on a central node, over a natively distributed architecture. We intend to provide a conflict resolution platform, but in a distributed and transparent way, as a NGF embedded on the architecture. A distributed agreement mechanism based on blockchain technology and self-enforcing smart contracts is envisaged to natively enforce security of transactions and to address the orchestration issues without relying on a central entity. Such a distributed agreement mechanism would allow to decouple controllers from end devices, enabling controllers with different goals to deploy actions over the same edge devices, while keeping global coherence. It represents an horizontal open infrastructure where devices from all product manufacturers and from several ecosystems can participate. Transactions are not tied to a specific domain or service, instead its purpose inside a household is for devices and services from different domains to exchange data and resources over the same infrastructure.

5.1.2 Distributed transaction mechanism using Blockchain technology

When two parties want to establish a digital transaction over a distributed network, they need to claim ownership of the digital assets involved and to ensure transactions are non-reversible, particularly when digital transactions comprise non-reversible physical services. Digital signatures together with some asset registry, provide a solution to the problem of ownership and authorization for spending assets, but do not solve the double-spending problem. Double-spending is a fundamental problem of digital currencies over distributed networks, which occurs when an entity that earns certain amount of digital assets transacts that same amount simultaneously to two other entities, and if there is no distributed way for determining which transaction arrived first, transactions can be easily reverted in the absence of a centralize clearing entity.

Bitcoin provided the best solution up-to-date for distributed agreements over ownership transfers and validity of transactions by establishing a chain of ownership. This mechanism is called the blockchain, as it groups transactions into blocks and chains them together using cryptographic technology, building up the transitions into current state of the database. From those technologies, Proof of Work (PoW) is the most relevant, as it makes it difficult for a node to publish a new block of transactions by tying the validity of a new block to the solution of a complex mathematical puzzle. The solution to the puzzle requires trial an error and difficulty is adjusted for blocks to be published periodically (In Bitcoin one block every 10 minutes approximately). This makes it very hard and costly for an attacker to fork the chain and introduce invalid transactions, as it needs to have more than half of the computing power of the network to carry an effective attack. As this mechanisms requires a lot of energy for maintaining the agreement on the network, there exist alternatives such as Proof of Stake (PoS), which are more efficient and may have similar security guarantees. Regardless of PoW or its main alternative PoS, our focus is on the blockchain, because it can be seen as a distributed, self-authenticating, time-stamped store of data, which in addition allows to execute code in a distributed and extremely reliable manner, and thus can be used for many things other than cryptocurrencies.

Ethereum is the most relevant project generalizing the usage of blockchain technology. It provides its own improved implementation of the blockchain (turing-completeness, efficient Virtual Machine,

and flexible data storage), which enables the implementation of Smart contracts permanently stored on the blockchain and not inserted on every transaction. A Smart contract in the context of blockchain can be seen as a modular, repeatable script, which can be used to build distributed autonomous applications. These scripts are compiled into very low level operation codes and stored in the blockchain's data store at a particular address. When a transaction is sent to that address the distributed virtual machine executes the script's operation codes and is able to use the data which is sent with the transaction [60].

5.1.3 A chain of ownership over resources to avoid conflicts

Conflicts can be seen as double-actioning a resource, where a resource is the control over a device, a set of devices or an environmental variable (e.g.: temperature) under certain context, i.e.: during a certain period of time. In order to solve the conflict, a smart contract is established to avoid two entities sharing the control of a certain resource at the same time. The smart contract structures the acceptable means of exchange of ownership over resources; conditions for transferring ownership are previously stated (e.g.: at device deployment time [5]) and automatically enforced. Once a controller sends a transaction acquiring the control of a device over a certain time horizon, it can be sure of being in power of the resource as any transaction to control the resource by another controller will be considered invalid by all nodes, unless a new transaction is made asking for the transfer of ownership on the resource to another control agent. In this case there should be a contract where the conditions for transferring ownership are previously stated and automatically enforced. A blockchain keeps track of the order of transactions and the chain of transactions keeps track of the changes of ownership enabling conflict resolution in a cost-effective, transparent and auditable fashion.

5.2 On-premises distributed enforcing of ECA rules

In addition to solving conflicts, such a distributed system based on state of the art cryptographic primitives can provide further benefits: the blockchain-based platform can enable enforcement of ECA rules entirely on-premises. Most of the manual and ECA control would be handled locally and autonomously by smart contracts running over the "unmanaged" blockchain. This will improve security, privacy and service availability (services do not necessarily rely on Internet connectivity or in energy supply). This will also enable connected device vendors to avoid paying, or to reduce the bill (reduced usage), for cloud infrastructure along the lifetime of the device (expected to last several years). Furthermore, such a mechanism could be implemented as part of middlewares (e.g.: Alljoyn architecture Base Service).

5.3 Challenges of a household blockchain

Given that cryptocurrency makes no sense in the interactions among household devices, one of the biggest challenges is to ensure the effectiveness of the consensus algorithm and the participation of devices for securing the network (e.g.: from Sybil attacks), which can be undermined by lack of incentives. As an alternative to digital currency we envisage a reputation token, representing the value device manufacturers provide by actively securing the network, enabling interoperability and distributed agreement.

Two other challenges that would need to be analyzed by further work are:

- The delay imposed by the network and the difficulty to publish a new block (time between blocks) are determinant to analyze the feasibility of using distributed agreement mechanisms for real-time applications at a household level, i.e.: the possibility of enabling micro-transactions at a speed fast enough to provide Event-Condition-Action (ECA) rule-based services involving

user interaction, and assess/minimize the impact of forks (inconsistency) on the interaction among devices and controllers.

- Blockchain-based distributed agreement are not continuously consistent as there will often exist forks from the main blockchain which will require some time window for the "voting" to happen and to be back in a "synchronous" state. The impacts of such forks on the interaction among devices and controllers needs to be assessed and minimized.

For the first issue there exists solutions such as the Lightning network and other similar technologies relying on the possibility to establish transaction channels created by a couple transactions on the blockchain that enable to secure any amount of micro transactions off the chain. In this case there would be no need to publish every transaction on the household blockchain and even some micro transactions can rely on channels created over blockchains outside the household such as at the neighborhood level or public ones. Note that Cosmos network promise to enable inter-blockchain communication, which could pave the way to such interaction among blockchains at different levels of a hierarchy similar to the telecom hierarchy where you have a LAN, an access network and the public Internet

6 Business model analysis

6.1 Current IoT business models are broken

With respect to the customer value, there are few value propositions that focus on user needs and go beyond connecting things. Most products are a consequence of a race for adding features which an average consumer might never find useful, but which may seem great for the early adopters or do-it-yourselfer. Regardless of reductions on manufacturing costs, final prices to consumers are still too high for a massive uptake, some including costly subscriptions. This is due to increased complexity in the design of devices, requiring more research efforts as well as diverse capabilities, and to the continuous costs in (cloud & communications) infrastructure needed to maintain device functionalities during product lifespan. Price would not represent such a barrier if there were a consistent provision of value to customers. Thus, there is strong competition to reduce final purchase prices and subscriptions while a large amount of investment is needed to implement and maintain related services. Furthermore, there is the missing revenue problem, due to the lack of appropriate business models or the use of unsustainable ones. Several business models relay on monetizing customer data, which may not scale if too many devices provide similar information and the market valuation is substantially reduced. Others rely one-time payment for smart devices which forces providers to sell a myriad of devices to break even, pushing to market devices that do not necessarily provide value to users or move towards expensive subscriptions for services that users would not end up using and would not be sustainable. According to IBM with respect to one-time revenue vs continuous cloud infrastructure costs: “Revenues have been relatively small . . . largely a result of the cost and complexity of most IoT solutions . . . treating the IoT as if it were just another computing platform, and applying the same set of business models: services, ecosystems, applications and analytics.” [48]. Continuous costs in infrastructure (including infrastructure as a service) needed to maintain device functionalities during product lifespan, lack of scalability (in the case of centralized server farms), reliability issues and threats to privacy are some of the challenges posed by the dependency on centralized or cloud-based resources. These issues call for a better distribution of data and intelligence, optimizing cloud usage by supporting storage and treatment of data closer to the edge in a more distributed fashion. A distributed middleware/abstraction layer providing interoperability among devices and applications will be essential for a better distribution of data and intelligence and will serve as a base for the upcoming of new sustainable business models.

6.2 New business models based on shared distributed platforms

It makes more sense for both users and service providers to pay in terms of the services that are provided. In this sense we could think of a business model in which services that require more data and more treatment will potentially provide more value to users and hence require more payment. In this scenario users would not have to pay for the Sensors/actuators needed to deploy services, bur rather pay for the service itself depending on the use of the service, such as in Infrastructure/-Platform/Software as a Service in the cloud business, except that in this case the sensing/actuating infrastructure will be payed by the service provider depending also on its use (the rate of data/transactions exchanged with the edge device). All these will be enabled by the fact that we can track the transactions on the distributed ledger and autonomously bill for transactions without the need to establish previous trust bonds among service providers and infrastructure providers.

This model of the Smart Home architecture would enable the use of recently published results [6] for the analysis of sustainability of IoT business models using game theory. In [6], authors provide an analysis of sustainability of business models for an oligopoly of service providers competing for subscribers (end users) and paying Wireless Sensor Networks. In our case service providers are represented by controllers in the smart home, while sensors actuators are the Wireless Sensor Network, which would allow us to draw some interesting conclusions on the conditions for the feasibility of business models under a shared distributed transactive architecture.

This would lead also to clear the way and to simplify users life as only useful services and sensors/actuators will be provided/suggested by service providers.

7 Conclusions and Perspectives

From the analysis of relevant technologies we conclude that, although low level communication protocols will continue evolving, mainly through improvements in security and energy efficiency, there will probably not be disruptive innovations coming from that space. There are only a few relevant wireless protocols for the IoT-based HAN: BLE, Thread (802.15.4/6LowPAN), EnOcean, RFID/NFC and iBeacon; each of which is better adapted for certain interface characteristics and implemented functions. With respect to application transport technologies, an IoT architecture must provide support for both pub/sub and request/response mechanisms, but current protocols implement natively one of such communication patterns, and the other as an extension (XMPP pub/sub extension or CoAP Observe capability), leading to complexity and inefficiency. Furthermore, security is also being added as an extension instead of being considered by design. Security for IoT must face the challenge of energy, storage and processing constraints of devices as well as the difficulty of establishing a trusted environment among a myriad of devices from different manufactures.

The local implementation of NGF allows for a better distribution of data and intelligence, enabling better enforcement of security and privacy policies, interoperability closer to the edge, improving efficiency, reliability, and user experience. In this regard, the major breakthrough is coming from the development of ecosystems such as AllJoyn and IoTivity, based on link layer agnostic platforms providing interoperability among devices from different manufacturers and applications from different service providers. Such platforms promise to ease developers lives and to create further value to customers, but there are plenty of other relevant application layer technologies providing a common language and basic services for end to end interoperability, such as HomeKit, more recently Weave, or the OneM2M standard that pretends to become the generic interworking framework. The competition among them may take years and will probably end by having some devices to support a couple of application protocols and acting as gateways translating among them.

The general architecture presented in this chapter should be optimized to provide simple, secure and efficient implementation of multi-pattern interoperable protocols, capable of handling event-

based/data-driven messaging and digital transactions. Regarding event-based messaging we consider that a content-centric approach may ease the implementation of such principles on our IoT architecture. With respect to digital transactions, an issue that will arise, as a consequence of the distribution of intelligence towards the edge and the heterogeneity of domains involved (health, energy, security, etc.), will be the lack of orchestration/federation mechanisms needed to provide conflict resolution, distributed agreements and enforcement of security of transactions in such a distributed environment. An optimized architecture should natively provide mechanisms for the orchestration of interactions among connected objects.

Chapter 3

Distribution Grid Energy Management Architecture

1 Distribution Grid Energy Management

1.1 Objectives of a distribution grid EMS

The main goal of a distribution grid Energy Management System (EMS) is to enforce efficiency, reliability and quality of energy supply, for which leveraging Distributed Energy Resources (DER) flexibility through Demand Side Management (DSM) mechanisms will be a main technological enabler. Thus, a distribution grid EMS architecture needs to enable the following functionalities:

Local energy balancing - Leverage coordination of DER to balance local production at the distribution level (neighborhood/village). This has the potential to alleviate congestion, reduce losses and consequently augment variable RES hosting capacity.

DSO "Reserves" - Enable Distribution System Operator (DSO) to influence flexible DER behavior for collaborating with voltage control and congestion management.

Wholesale Market participation - Maintain collaboration with global objectives for grid balancing, through actors participating in the wholesale market, such as suppliers and aggregators.

Value to customers - The prosumer side of the participation on all the previous mechanisms needs to be taken into account and the allocation of DER to such mechanisms needs to be optimized for customer goals and policies; e.g.: minimizing impact on privacy, ease of life and comfort.

1.2 Requirements for a distribution grid EMS

The requirements for a distribution grid energy management architecture are the following:

- Reliability/Fault Tolerance - In order to leverage DER flexibility, any solution that tends to distribute the intelligence will need to maintain system reliability and fault tolerance. In this

context, the EMS architecture must continue working under communication errors, or under presence of node failures or byzantine nodes.

- Flexible and Extensible - Flexible and extensible implies Plug and Play capabilities, which enable seamless integration over time [61], i.e.: handle continual arrival and departures of appliances, resources and control agents at different levels of the architecture.
- Scalability - There are a multitude of DERs, spawned over distant geographic areas, owned by different actors. Various market players, each one with its own objectives, are interested on leveraging those resources at different time scales. The EMS architecture needs to cope with the scalability issues in terms of time, scope and heterogeneity of resources and involved actors.
- Trustworthiness - The actors in charge of the EMS or the energy management mechanisms and their implementation need to be trusted: This implies Transparency, Security and Privacy on the transactions among participating actors. With respect to transparency, visibility over DER at the distribution level is becoming increasingly important to avoid system imbalances.
- Low Implementation and Maintenance Cost - Business models are not yet clear, as pricing schemes and flexibility value characterization are still being studied, so the costs imposed by the energy management mechanism must be minimized.
- Re-usability of Infrastructure and platforms across distribution grids (Energy, Water, Gas, Heat). Re-usability of infrastructure and technologies should be aimed whenever possible, as a matter of costs but also due to interoperability, cross resource services (Combined Heat and Power management), critical mass of experts, etc.
- Independent evolution of control strategies. The architecture should enable the independent evolution of control strategies at different levels (Household, Distribution Grid, System Level), to cope with the fast progress of technologies and control mechanisms.
- Efficiency and equity. In order to maximize social welfare, energy management mechanisms should maximize the value extracted from flexible resources and provide a fair distribution across participants, according to the service definitions. Furthermore, economic efficiency is required to incentive actors participation.

1.3 Current approaches for DER management

The two main approaches to manage flexible DER, both in literature and in practice, have been Microgrids and Virtual Power Plants (VPP)s. Microgrids are defined as an entire partition of the physical infrastructure, with a Point of Common Coupling as unique interface with the hosting grid. This enables the possibility of isolation, but requires a unique actor to manage electricity flows exchanged with the hosting grid and economic transactions into the wholesale market (Figure 3.1). For this reason, Microgrids are a good model for a university campus or small communities. However, in the general case, there would be several actors (suppliers, aggregators, etc.) participating individually on wholesale markets by aggregating DER from the distribution grid. Thus, if we were to consider the Microgrid approach as the canonical method for distribution grid energy management, we would need to redefine the roles of DSO, aggregators and current Balancing Responsible Entities (BRE), and to adapt wholesale market rules accordingly.

On the other hand, VPPs are focused on wholesale market participation as a replacement of conventional power plants, and for this they aggregate DER flexibility from across several distribution grids. VPPs are implemented through contracts with flexibility DER owners, obtaining the exclusive control of physical devices. In consequence, the corresponding DER are not available, neither visible

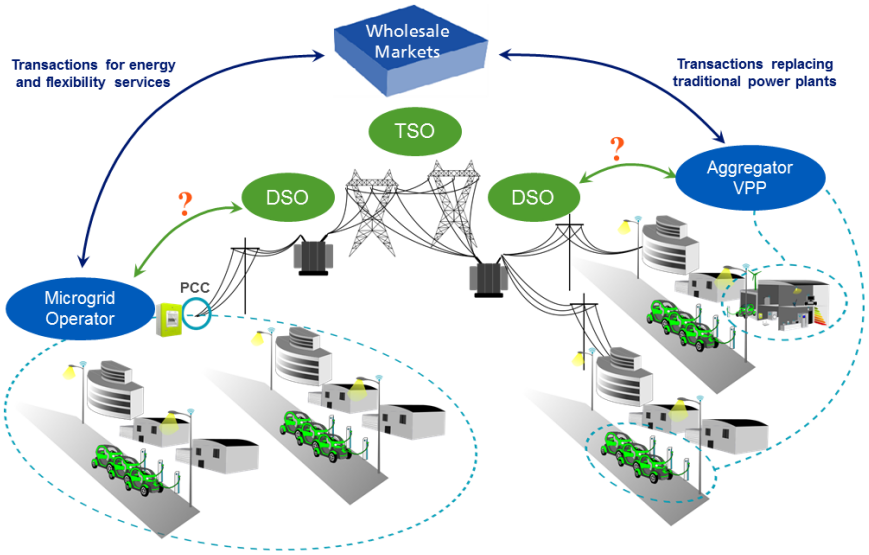


Figure 3.1 – Microgrid and VPP approaches to DER management

to third parties. This lack of visibility may have negative impacts in grid balancing if there is no coordination among actors. VPPs play a major role in the participation of DER in wholesale markets but they do not have a clear role at the distribution level and may not take into account distribution grid constraints. Other papers have considered coordination among VPPs and DSO: [62] assumes that "a sort of local market is established" in order to be able to coordinate the concurrent operation of DSO and VPP through appropriate economic signals. While the Fenix project defines a Technical VPP which clusters RES from the same geographical area and would need tight coordination with the DSO [63]. To the extent of our knowledge, current literature about VPP has not addressed a general way of coordinating DER participation on wholesale markets with distribution grid needs.

2 DSM Architecture Proposal

The electricity distribution grid was not designed to cope with load dynamics imposed by high penetration of electric vehicles, neither to deal with the increasing deployment of distributed Renewable Energy Sources. DSOs will increasingly rely on flexible DER (flexible loads, controllable generation and storage) to keep the grid stable and to ensure quality of supply. In order to properly integrate demand-side flexibility, DSOs need new energy management architectures, capable of fostering collaboration with wholesale market actors and prosumers. We propose the creation of *Virtual Distribution Grids* (VDG) over a common physical infrastructure, to cope with heterogeneity of resources and actors, and with the increasing complexity of distribution grid management and related resources allocation problems. Focusing on residential VDG, we propose an agent-based hierarchical architecture for providing DSM through a market-based approach, where households transact their surplus/lack of energy and their flexibility with neighbors, aggregators, utilities and DSOs. For implementing the overall solution, we consider fine-grained control of smart homes based on Internet of Things technology. Homes seamlessly transact self-enforcing smart contracts over a blockchain-based generic platform. Finally, we extend the architecture to solve existing problems on smart home control, beyond energy management.

2.1 Virtualized Distribution Grid

Current approaches for the management of DER fail to take into account the coordination at the distribution grid level across multiple actors as they focus on the aggregation of resources for participating on the wholesale market. Thus, we propose a new architecture for distribution grid energy management, with the goal of coordinating the usage of flexible energy resources among different actors. The approach is compatible with Microgrids and VPPs, as it does not targets wholesale market participation, but requires Microgrids and VPPs to negotiate the access to flexible DER through the corresponding resource allocation mechanism. Any other future system aimed to leverage flexible DER in wholesale markets would need to interact with such coordination mechanisms. As a consequence of aiming neutral resource allocation mechanisms, the distribution grid can be transparently managed, offering visibility for all relevant grid actors.

The resource allocation mechanisms need to cope with several types of flexible resources, with a wide scope of characteristics. Such resources are owned by various types of self-interested actors (residential, commercial and industrial prosumers, Electric Vehicles (EV) charging stations, energy service providers, aggregators, etc.), whose objectives are not necessarily aligned with distribution grid needs. To cope with the complexity of such mechanisms, we propose the creation of VDGs in charge of the energy management of subsets of resources by type and corresponding actors, over common distribution grid infrastructure. Each VDG will require different architectural building blocks and specific management policies and algorithms, e.g.: we could envisage a VDG for management of DER from residential prosumers in a neighborhood and another for managing EV charging on a feeder (Figure 3.2).

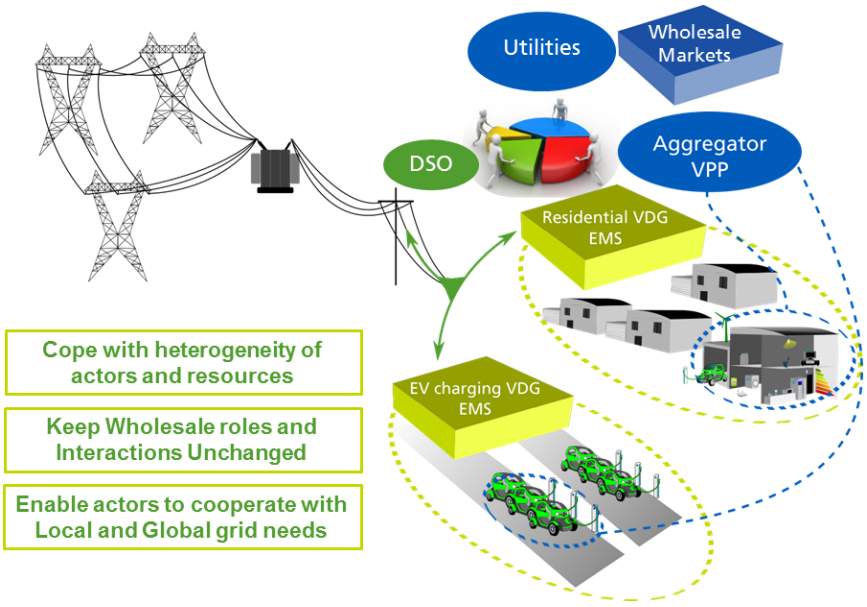


Figure 3.2 – Virtual Distribution Grids approach to DER management

This is similar to the approach used on cloud environments to optimize the allocation of physical resources (processing power, storage or bandwidth), where a native hypervisor enables the creation of various virtual machines over a shared physical infrastructure. Every virtual machine needs an Operating System (OS) to access logical resources through the corresponding drivers. Additionally each OS will have algorithms to efficiently allocate available virtual resources to applications. An OS

provides an execution environment to application programs, abstracting the low level complexity of resources from users and application developers (through user-spaces and Software Development Kits respectively).

Back to the energy management problem, the role of the DSO is analogous to the one of an hypervisor, in charge of keeping a coherent global behavior between infrastructure management and energy management. DSOs would monitor physical resources and impose constraints to the each VDG[1] resource allocation process or incentive behavior of actors through a reserve mechanism. We can imagine that some VDGs would have more priority than others in the context of congested distribution lines, and by prioritizing, DSOs could even offer differentiated grid connection services.

The notion of OS on a VDG would be that of an EMS architecture[2] providing visibility and control over DER, by enabling its allocation to the different possible usages, in a similar way an OS allocates processing power to applications on a virtual machine. The main "applications" that will compete for DER should enable power balancing inside the VDG, participation in existing wholesale market mechanisms, and providing services to the DSO for voltage and congestion management. Actors foreseeing those uses will probably be competing for flexible resources in the same time-slots where the grid needs them more and flexibility has more commercial value. The EMS architecture needs to provide a cost-effective, transparent and secure coordination mechanism to allocate flexible resources to maximize social welfare; i.e.: to provide an equitable (e.g.: max-min fairness) and efficient (e.g.: Pareto efficient) allocation. In the following we will focus on the EMS of a particular type of VDG rather than on the role of DSO as an orchestrator of real and virtual resources. We will analyze general aspects of the design of an architecture capable of providing such an allocation of distributed resources.

2.2 Design of a Residential VDG

In this work we focus on the EMS of residential VDGs, i.e: on the management of flexible DER from residential prosumers in a neighborhood/feeder. In particular, we are interested on locally balancing distributed renewable energy production by leveraging Internet of Things (IoT) technologies to communicate, monitor and control flexible residential DER. For the design of the residential VDG energy management architecture we will consider special attention to interoperability among architecture implementations, distribution of intelligence, security and privacy requirements, as these aspects play a major role on the viability of an IoT-based architecture.

2.2.1 Hierarchical Architecture

Centralized approaches for distribution energy management rely on a unique entity that must gather data, perform calculations and determine set points for every controlled resource. A centralized approach provides optimality at the expense of extensive communication and computing resources and lack of flexibility and adaptability. Furthermore, a central fully informed entity may not be available due to natural information asymmetries and selfish participants, i.e.: DER belong to different actors and decisions are made locally to optimize owner's objectives [64]. Additionally, certain information is only available locally due to privacy concerns, such as presence information. Thus, it is hard for centralized control to handle customer policies based on context awareness, such as comfort or auto-consumption policies.

On the other hand, fully decentralized approaches that take decisions using local information without coordination can lead to synchronization and oscillation of the overall response. In particular,

[1] Note that there is no complete isolation among VDGs due to the correlation created by voltage variations. We are currently analyzing mechanisms for coping with such issues.

[2] Note that the implementation of the EMS functions will run over an OS, but that is not what we are discussing here.

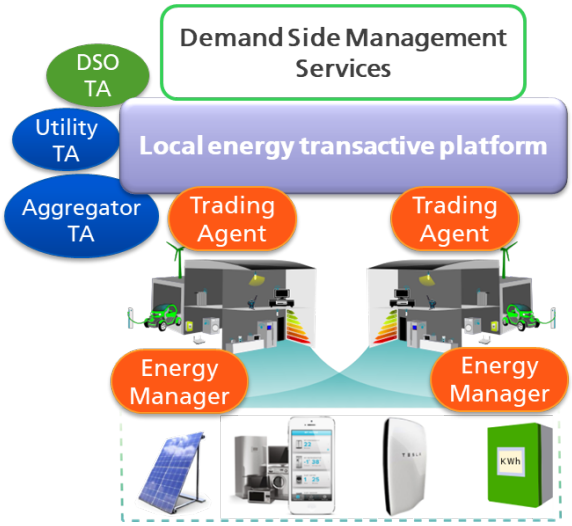


Figure 3.3 – Hierarchical architecture for distribution grid energy management

there exist already plenty of technologies enabling a more efficient usage of electricity and promoting auto-consumption for households that count on local PV production and/or storage facilities. These systems may not take the needs of the grid into account and affect the way utilities (and other BRE) balance customer demand and market supply, as their statistical models for load forecasting would not be valid any longer. Therefore, unless managed appropriately, such systems may create stronger and recurrent imbalances on the grid.

Even if the geographical extent of a residential VDG is not large, we still have a considerable number of controllable resources with stringent performance requirements, in terms of high-speed communication and computation of actions/set points for every unit [61]. A hierarchical approach would drastically reduce such requirements for data gathering and processing, and would enable the independent evolution of control strategies and technologies by defining clear interfaces among levels (like through Application Programming Interfaces). Thus, we propose a mix of control strategies composing a hierarchy of three levels: the control inside each household, the allocation of prosumer resources at the distribution grid level and the Transport level that controls the overall grid balance.

We will focus on the two lower levels, as wholesale market and Transmission System Operator (TSO) control mechanisms, in spite of their continuous evolution, are more mature and reliable than the rest of control levels. Furthermore, we want to avoid requiring changes from the higher level other than small changes for the actors participating in the market, i.e.: on the way suppliers and aggregators gain access to flexible DER.

2.2.2 Household Control level

Households represent the base of the hierarchical architecture for coordinating the allocation of DER resources to the different Demand Response (DR) mechanisms depending on customer policies and economic incentives. In particular, security and privacy policies would lead to keep sensible data under the control of the customer to gain trust and acceptance. In order to enable such an empowerment, the distribution of data and the intelligence required for its treatment need to be designed accordingly. Considering a separate level for the energy management of a household enables such a distributed intelligence approach.

Each household will have an energy management function, called Home EMS (HEMS), providing

coordination among flexible loads, storage, local production and energy consumed from the global grid or from the VDG. Each HEMS will have its own knowledge and individual goals, and the capability to transact resources with the upper levels through a trading agent. The trading agent will abstract heterogeneity of household control implementations from the distribution grid level, i.e.: one agent representing the global goals of the smart home regardless of the coordination and control mechanism implemented inside each household.

2.2.3 Distribution Grid Control level

In order to optimize the scheduling and dispatch of DER, coordination among households, DSO and other grid actors is mandatory. We envision the implementation of market-based mechanisms, enabling coordination and collaboration among trading agents representing households, DSO and other grid actors through the exchange of energy transactions (Figure 3.3). Agents will transact energy resources with each other in order to meet household economic and comfort goals, while collaborating with local and global grid infrastructure operation issues[3]. Markets have proven to be a suitable mechanism for resource allocation and control of autonomous selfish parties, and have already been tested for Distribution Grid Energy Management in the US, following the Transactive Energy approach [65], and in Europe under several demonstrator projects generally involving Microgrids [66] [67] [12].

DSOs will implement agents representing the infrastructure needs from each VDG, for maintaining power quality and security constraints. This agent will be fed by the global distribution management system with day ahead operational requirements and by Supervisory Control And Data Acquisition (SCADA) system with information about grid conditions and reliability requirements for real time distribution automation.

BREs and other actors participating wholesale markets will be represented by agents on every VDG of the low voltage distribution level. This will enable those entities to gain feedback on the behavior of the households comprised on their balancing domain and to better manage the aggregation of several sectors to provide services and to optimize their demand portfolio on the wholesale markets.

All previous processes need to take into account the economic scheduling and dispatch of DER resources in order to encourage participation on the EMS. Though business models are out of the scope of this work, we consider current economic signals are not favorable in most European countries for exploiting DER flexibility, but we assume they will evolve towards a more encouraging context.

2.2.4 Wholesale Market-adapted Timescales

Until now we have addressed the architecture hierarchy in terms of space or control areas and now we will consider the timescales in which energy resources would need to be allocated. We will consider three time scales, day ahead, intraday and real time, in order to adapt the allocation of flexible capabilities to the market structure and to ease the interaction among levels.

Day-ahead process - On the day ahead process, each HEMS will estimate the surplus or lack of energy for every hour of the next day, based on consumption and production forecasts. Then, the expected imbalance can be eliminated/minimized by scheduling controllable appliances or can be traded in the VDG market with other households or with actors participating on the wholesale market. The HEMS will decide the volume of electricity to be traded on the market with the corresponding price cap, by optimizing the scheduling of controllable appliances taking into account economic incentives (price of electricity supply, aggregator offers, feed-in tariffs, etc.) and customer policies (e.g.: comfort constraints).

[3]We assume the necessary regulation is in place to allow households to establish transactions among them for the exchange of energy.

The trading agent representing each household will send the corresponding bids and asks to the VDG market, which will match the orders determining the volume and price of equilibrium for each hour of the day. This process should finish earlier than the Day-ahead wholesale market, as the energy that was not balanced on the local market needs to be provided/absorbed through the wholesale markets or Over The Counter agreements, and the flexibility resources that were not traded on the local market remain available to the wholesale mechanisms.

Intraday process - The intraday process in each household will detect variations from the expected day-ahead load/production schedule and to allocate those gaps to the remaining local flexibility budget or to intraday VDG market mechanism. The VDG intraday market mechanism works in a similar way to the wholesale mechanism, where BREs can aggregate traded volumes and offer them to the balancing mechanism, the intraday energy market, or can exchange blocks with another balance responsible party in order to avoid paying penalties to the TSO. Thanks to this mechanism DSOs will have the capability to avoid congestion, reduce losses or control voltage by influencing demand-side energy behaviors, e.g.: by building a distribution grid reserve.

Real-time process - In the real-time process, controllable loads need to fulfill the transactions they applied for in day-ahead and intraday, and the aggregators/BRE need eventually to execute balancing orders transmitted by the TSO in response to accepted bids on the balancing mechanism. In a similar way to previous processes, we will try to eliminate imbalances or to trade them into the market, but in this case the imbalance is measured with respect to an objective that depends on the mechanism to which resources were allocated. For example, if resources were allocated to an aggregator participating to the adjustment reserves, the objective will be to reduce/augment the energy consumed with respect to the last half an hour; while if resources were allocated to a distribution system reserve the objective may be to follow a curve provided by the DSO. The real time mechanism is not to be confused with *Primary Control*, which is autonomous frequency and voltage control, and the fastest response to stabilize the grid under system dynamics. In this work we assume the physical resources attributed to the VDG are grid-connected and thus *Primary Control* is assured at system level, i.e.: we do not consider isolation of physical resources.

3 Transactive platform implementation

Creating distributed transactive applications for the secure and transparent exchange of assets over a shared infrastructure formed by a network of competing parties has recently become feasible thanks to blockchain technology. The network is composed of validator nodes, for instance implemented by operators and service providers, in charge of forwarding and processing transactions into blocks, and validating the addition of new transaction blocks on a shared ledger. This shared ledger works like a replicated state machine, in which a new block represents a distributed agreement on its next state. The ledger can host code in the form of a smart contract [60], which is executed each time a transaction gets addressed to it. This behavior is replicated across validator nodes, and allows the system to process transactions securely and reliably even in the presence of malicious nodes (Byzantine fault tolerance).

We use blockchain technology to build a chain of ownership over energy resources, i.e.: energy/flexibility units, so these can be traded in advance, in exchange of money in the form of a token payment. The parties involved in a transaction also receive the extra FIT reward as described in Section 2.2, as long as the enforcement of the corresponding electricity flows is validated by DSO[4]. Such

[4]Such verification could be automatically done by smart meters.

rewards are made through a token we call ECOin, representing a certificate of green energy traded locally, which can have many applications related to energy efficiency or CO2 emission reductions.

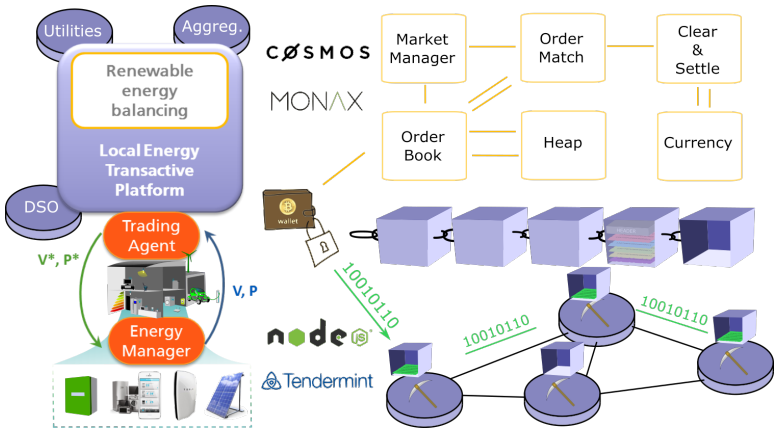


Figure 3.4 – Blockchain-based transactive platform and market implementation.

We used networks of Smart Contracts to implement each aspect of the market as exemplified on Figure 3.4, including registries (Renewable energy registry), matching offers (through implementation of auction mechanisms), clearing and settlement of transactions (verification of flows and attribution of tokens). The Monax platform was used to create the network of validator nodes, which achieve distributed agreement thanks to the Tendermint Byzantine Fault Tolerance algorithm [60]. Monax provides also the tools to deploy smart contracts and Node.js libraries that were used for the Trading Agents to interact with the network of validators.

In addition to the local balancing markets, the distributed nature of blockchain-based markets will enable any aggregator or supplier to offer complementary demand response services. For instance, the deployment of bi-level optimization mechanisms considering competing aggregators, such as in [68], could be done through smart contracts enabling prosumers to transact their flexibility without the need of having a previously signed legal contract. Furthermore, the shared transaction history could be used as a source of reputation of the different service providers as well as of the prosumers.

4 Conclusions and Perspectives

Major ongoing evolutions in the electricity industry potentially represent a key driver for the Energy Transition and related objectives. Nevertheless, they impose new challenges in the whole value chain. The required transformations of the Distribution grid are today delaying, and in some cases blocking, the possibility to leverage key opportunities. In this chapter we propose a new paradigm, that we named Virtualized Distribution Grids, which facilitates implementing the required solutions for major distribution grid challenges without requiring important infrastructure investments. The proposal includes a new approach for designing DSOs' Energy Management Systems. The hierarchical architecture we present enables the coordinated participation of any type of player, including DSOs, aggregators, and end users (that become *prosumers*). In addition, in this general framework, we propose specific *market-based* solutions that enable deploying advanced technologies (local production, storage, building EMSs, IoT based demand response systems and other on-premises technologies), by different players, and coordinating those players in a way to optimize the overall value while keeping the distribution network stable and providing the expected quality of supply. In addition, we present a distributed architecture, based on blockchain technology, that supports the implementation of the

proposed markets and satisfies the requirements for future energy management architectures, particularly in terms of infrastructure mutualization, reliability, security, transparency and auditability..

Part III

Innovative services enabled by the architecture

Chapter 4

Renewable Energy Balancing local Market

1 Introduction

Future electricity distribution grids will host a considerable share of variable Renewable Energy Sources (RES) and local storage resources. Moreover, they will face new load structures due for example to the growth of the electric vehicle market. These trends raise the need for new paradigms for distribution grids operation, in which Distribution System Operator (DSO) will increasingly rely on demand side flexibility and households will progressively become prosumers playing an active role on smart grid energy management. However, in present energy management architectures, the lack of coordination among actors limits the capability of the grid to enable the mentioned trends. In this chapter we tackle this problem by proposing an architecture that enables households to autonomously exchange energy blocks and flexibility services with neighbors, operators and market actors. The solution is based on a blockchain transactive platform. We focus on a market application, where households can trade energy with their neighbors, aimed to locally balancing renewable energy production. We propose a market mechanism and dynamic transport prices that provide an incentive for households to locally manage energy resources in a way that responds to both prosumer and operator needs. We evaluate the impact of such markets through comprehensive simulations using power flow analysis and realistic load profiles, providing valuable insight for the design of appropriate mechanisms and incentives.

In this chapter we propose a novel cost effective architecture that, on the one hand, enables households to autonomously exchange energy blocks with their neighbors in order to optimize their electricity bill, and on the other hand, enables the DSO to induce a global behavior that supports the stability of the network, by favoring the balance of the excess of renewable energy with flexible demand at the neighborhood level.

The architecture relies on local energy markets, for which we propose an auction mechanism in charge of the efficient matching of households offers to buy and sell renewable energy. We exploit dynamic transport fee rebates for creating incentives for households to adapt their demand of electricity to the availability of local renewable energy production. Proposed mechanisms have the potential to alleviate congestion, reduce losses and consequently augment RES hosting capacity.

To implement the market we propose a blockchain-based transactive platform designed to enable the trustworthy execution of transactions among actors, thanks to increased security and transparency

with respect to a centralized auctioneer, leading to simplified and automated system audits [60].

We developed a proof of concept realization of the proposed market mechanism, which allows us to evaluate the impact of local renewable energy markets on distribution grid quality of supply through comprehensive simulations using power flow analysis and realistic load profiles.

The main contributions of our work are the following:

Section 2 - Local renewable energy balancing markets : We propose the transaction of energy among households through a market aimed to locally balancing the excess of renewable energy production with flexible demand in the context of future low voltage distribution systems.

Section 4 - Market mechanism and price incentives : We propose an auction mechanism that is asymptotically efficient, truthful, weakly budget-balanced, and fair in the attribution of quantities. Additionally, we use simple transport fee rebates to incentive houses to locally control their flexible demand in a way that benefits both prosumer[1] and DSO.

Section 6 - Distribution Grid impact assessment : We thoroughly assess the impact of markets on distribution grid quality of supply. For this, we consider a broad set of metrics (Section 3) and we provide a simple but comprehensive model for the household optimization problem (Section 5).

1.1 Related Work

Markets mechanisms have proven suitable for resource allocation and control of autonomous selfish parties [69], with multiple applications on the energy domain such as for demand side management [70] [32, 71]. Previous work on the exchange of energy among households has mainly focused on continuous double auctions[2] [7,8], which are hard to implement over a distributed platform that lacks fine-grained transaction arrival ordering, while call markets in which orders are matched periodically [9, 10], are better adapted and can also be more efficient [11], though [9] does not account for neither auto-consumption nor batteries and [10] proposes a complex multi-round hybrid mechanism. A market maker was proposed in [72], with the aim of flattening the aggregated energy profile by setting a price for energy that depends on the deviation of households from their expected average profile. We believe that penalizing deviations from the average demand profile is not a good approach, as such deviations may benefit both the DSO and the prosumer. Most articles taking into account the impact of such markets on the distribution grid rely on locational marginal pricing [12, 13, 73] or message passing [14], which requires specific knowledge on network topology and may penalize households depending on their location. Others consider capacity constraints or convex operator costs on a Microgrid context where a centralized agent defines the aggregated flows.

There is a recent trend towards local/micro markets for the exchange of energy among households over distributed platforms, up to the extent of regulation being adapted to support those approaches [74].Current blockchain-based approaches[3] are still in its infancy. They are not taking existing distribution grid needs into account, or they are trading renewable certificates rather than balancing renewable energy locally [15]. The challenge resides in finding the right incentives and defining the appropriate mechanisms for satisfying both prosumer and distribution grid needs, in a distributed way.

[1] Consumer evolution towards pro-active participation on grid activities.
[2] Buying or selling offers are matched as they arrive in the order of arrival.
[3] http://brooklynmicrogrid.com, https://powerledger.io, http://solarcoin.org

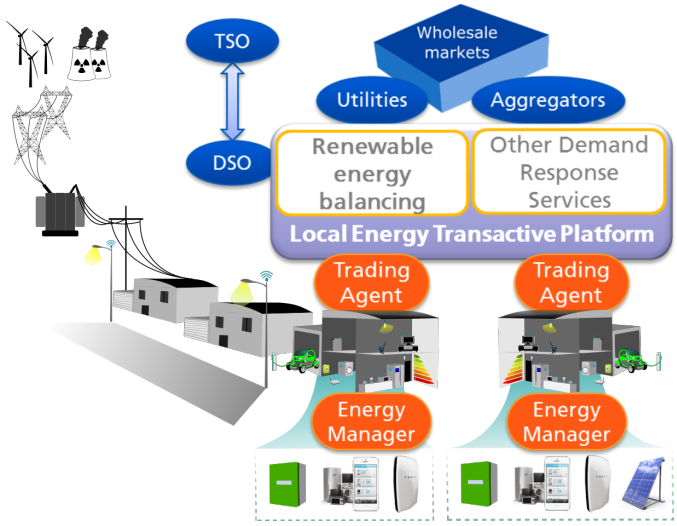


Figure 4.1 – Hierarchical architecture for distribution grid energy management.

2 System description

The physical architecture of the low voltage distribution grid under study consists of one Medium Voltage (MV) to Low Voltage (LV) transformer and one or more feeders to which residential prosumers are connected[4], as shown in Figure 4.1, in a context with high deployment of PhotoVoltaic (PV) Panels and rechargeable stationary batteries. We consider houses with a PV panel and a battery, houses with only a battery and houses without battery or PV panel, but with flexibility from controllable loads; all three types of houses count on smart meters[5]. We assume the flows from the PV and to/from the battery can be controlled by means of smart inverters [75]. This enables household to control the destination of the excess of renewable energy as well as the source of the energy that satisfies load demands. Other physical components that may be present on the smart home architecture are sensors providing information on energy usage to feed the forecasts and actuators over appliances/devices (windows) for fine grained control of the energy consumption, as well as the physical gateway described in Chapter 2.

Households interact with each other and with DSO, suppliers and service providers on the LV distribution grid through a local energy transactive platform, as was described in Chapter 2, to coordinate the access to Distributed Energy Resources (DER)[6]. These actors are represented by agents autonomously transacting energy resources with each other in order to meet their economic goals, while collaborating with local and global grid infrastructure operation. Households count on an energy management function (Home Energy Management System (EMS) (HEMS)) for optimizing the allocation of DER depending on consumption and production forecasts, prosumer policies, and economic incentives. Then, a Trading Agent function is in charge of exchanging energy blocks and flexibility resources over the transactive platform. Note that, as described in Chapter 2, these are *Cloud Functions* (CF), with HEMS being of Personal Cloud type doing forecast and optimization, while the Trading Agent is more of a Smart Object type implementing Event-Condition-Action (ECA) rules.

We assume the interoperability among those functions and their implementation on physical devices inside the household is obtained thanks to a middleware such as IoTivity, as was described in

[4]This can also be seen as a Residential Virtual Distribution Grid, as introduced in Chapter 2.

[5]We consider French distribution grids in particular, where smart meters are being massively deployed and specific regulation with respect to auto-consumption at the neighborhood level has been recently introduced [74].

[6]Flexible loads, controllable generation and storage resources.

Chapter 2, which abstracts the functional logic from the complexity in terms of low layer protocols (e.g.: Thread for sensors and actuators, and Bluetooth Low Energy (BLE) for user interaction and to obtain data from the smart meter through the BlueTic [22]).

2.1 Local renewable energy balancing markets

This chapter focuses on renewable energy balancing markets at the neighborhood level, where households can exchange their excess/lack of energy. Based on the forecasted gap between consumption and production and on their flexibility budget, the HEMS defines the energy available to trade in order to minimize the electricity bill. Then, the offers received from households' Trading Agents are matched by an auction algorithm that defines the accepted quantities to be exchanged and corresponding prices. The flexibility budget depends only on the available battery capacity[7] and not on flexible loads, so that there is less impact on comfort and minimal user interaction is required. This means that houses without battery make offers based exclusively on their expected gap between consumption and production, while the flexibility from elastic loads is reserved to enforce market commitments by absorbing forecast errors[8].

In terms of time scales, we focus on intra-day exchanges for energy blocks corresponding to 10 minutes periods, which would enable to timely update forecasts. Each market period will achieve finality at least one hour ahead of the time for which the resources are being allocated. This provides time for market actors to adapt their wholesale market offers, as the energy not balanced locally is provided/absorbed by utilities.

In order to evaluate the potential of proposed markets to augment variable RES hosting capacity, we need to consider appropriate quality metrics (Section 3). In contrast with data networks, electricity is not blocked or delayed by lack of capacity, as distribution grids tend to have a relatively low utilization factor; while supporting high maximum flows increases losses, reduces transformer and cable lifespan and can cause voltage issues. For this reason, rather than focusing on capacity, we consider aggregated and maximum flows through the transformer, the peak to average ratio (PAR), and respective losses; while for the lines we also analyze losses as well as voltage deviations and network imbalance.

2.2 Prices and auto-consumption

In coherence with a context of massive deployment of RES, we assume that parity has been achieved, i.e.: electricity prices are higher than the Levelized Cost of Electricity (LCOE) produced by PV panels. We consider the Feed In Tariff (FIT)[9] to be lower than electricity prices, leaving a gap that can be exploited to establish a market for the exchange of energy among households. In this context, we assume houses will always prefer to auto-consume the energy available from their PV panel. Then, in cases of excess of production (resp. demand), households would have the following options for the surplus (resp. lack) of energy: they can charge (resp. discharge) their battery, inject on the grid for the FIT (resp. buy it from the utility) or sell (resp. buy) on the local renewable market.

Considering low FIT has two main motivations, first the reduction on LCOE from PVs and the related increase in their deployment, and second, the need to incentive injection of renewable energy only when provides value to the grid. We propose that the gap between current FIT[10] and the FIT

[7] Available battery capacity refers to the share of total capacity available for energy trading, it usually corresponds to a State of Charge (SoC) between 20% and 80% of the total battery capacity, which enables to preserve the battery lifespan.

[8] We are aware that forecasts may deviate considerably and that it may be difficult to completely absorb the error with demand flexibility. Nevertheless, a sensibility analysis and eventually a stochastic approach are to be part of future work.

[9] The FIT is the regulated price that utilities must pay to prosumers for the energy they inject on the distribution grid.

[10] Current FIT values in France are around 3 times the price of electricity, regardless of the suitability of the injection for the distribution grid.

assumed by this work, could be used as an extra incentive for locally balancing renewable energy. Thus, only the energy that is certified to be balanced locally (thanks to the market) gets the extra feed in rewards; simultaneously motivating agents to enforce their contracted quantities through the local market. Furthermore, compared to current FIT, our approach not only benefits those who invest in PV panels, but also those who provide the flexibility necessary to host RES. Nevertheless, this incentive is not enough to take into account the needs of the DSO, as dynamic incentives need to be provided for households to charge their batteries when there is local renewable energy available. Such incentives will be proposed in Section 4.1.

3 Metrics for evaluating market impact

In this section we describe the quality metrics considered for the evaluation of the proposed renewable energy balancing market. We consider periods of 24 hours, slotted in time slots of 10 minutes duration, $t \in \mathcal{T} = 1, ..., T$, where $T = 144$ is the total amount of time slots. Let $P_{in,t}$ be the power flowing through the transformer from MV towards LV at time slot t, expressed as $P_{in,t} = \sum_{ph} \max(P^P_{ph,t}, 0)$, where $P^P_{ph,t}$ is the power on the primary windings for phase ph, and $P_{out,t} = \sum_{ph} \max(-P^S_{ph,t}, 0)$ the flow from LV to MV, where $P^S_{ph,t}$ is the power on the secondary windings. The total power traversing the transformer is given by $P_{abs,t} = P_{in,t} + P_{out,t}$. Given the flows through the transformer we define corresponding losses as follows:

$$Tr_{loss} = \sum_t (P_{abs,t}(C_L + C_C)) \tag{4.1a}$$

$$L_{loss} = \sum_{l,ph,t} R_{l,ph} I^2_{l,ph,t} \tag{4.1b}$$

where C_L and C_C are the coefficients representing leakage inductance losses and copper losses due to currents flowing through transformer windings, respectively. On the line losses, $R_{l,ph}$ is the resistance of the phase ph of section l of the distribution lines, and $I_{l,ph,t}$ the corresponding current.

With respect to the peak of power through the transformer:

$$P_{max} = \max(P_{abs,t}) \tag{4.2a}$$

$$PAR = T \frac{P_{max}}{\sum_t P_{abs,t}} \tag{4.2b}$$

RES hosting capacity is affected also by voltage issues such as maximal deviations of voltage from its nominal value as well as network imbalance[11]. The nominal value V_U and the voltage deviation V^{ph}_{delta} for each phase ph are defined as follows, with V^{ph}_{L2N} being the line to neutral voltage:

$$V_U = \frac{410}{\sqrt{3}} \tag{4.3a}$$

$$V^{ph}_{delta} = 100 \frac{|V^{ph}_{L2N}| - V_U}{V_U} \tag{4.3b}$$

$$VUF = 100 \frac{|V_2|}{|V_1|} \tag{4.3c}$$

Where V_1 and V_2 are the positive and negative voltage as per the symmetrical components method for unbalanced power systems and VUF is the Voltage Unbalance Factor.

4 Market mechanism

The role of a market mechanism is to determine the final quantities and prices traded by each participant, by matching their orders. The exchange of energy blocks among trading agents will be carried

[11] Refers to the uneven distribution of flows across phases. Also called Voltage unbalance.

out in a call market, through a Multi-unit Double Auction (MDA) mechanism[12] [11], where agents submit a bid or ask order, which are respectively the maximum, or minimum, price the agent is willing to pay to buy, or to accept to sell, the corresponding units of energy on certain time slot. We propose a discrete-time MDA mechanism based on the algorithm proposed in [18], a variation of which has already been used for energy allocation markets in the context of electric vehicle charging [76] and complies with certain interesting characteristics:

- Strategy-proof with respect to reservation price - Each agent's optimal strategy is to reveal truthful information regardless of other agents actions.
- Weakly budget-balanced - All payments between buyers and sellers sum to a positive value, which is used to reward the nodes that process the transactions.
- Individually rational - The market encourages participation by ensuring non-negative profits.
- Asymptotically efficient - The market becomes more efficient with the increasing amount of participants, maximizing total profit obtained by all participants.

The market will work on daily periods with one round to decide for each 10 minute time slot, during which the offers are considered static. For any given round, each buyer i submits a bid for v_i^b units at a reservation price of p_i^b and each seller j an ask for v_j^a units at p_j^a. The mechanism first generates the demand/supply curve, which sorts bids and asks in decreasing and increasing order of their reservation price, respectively. Then a buyer B and a seller S are identified at the critical point where the aggregate demand and supply meet. In order to make the mechanism strategy proof [18] the corresponding houses do not participate in the trade, as well as the offers with index over B and S. As a consequence of eliminating the critical offers, there are two cases for attributing quantities.

Let the aggregated volumes of participating bids and asks be $V_B = \sum_1^{B-1} v_i^b$ and $V_S = \sum_1^{S-1} v_j^a$ respectively, then if $V_B \geq V_S$, all sellers with index $j < S$ trade their volume v_j^a at price p_S^a, while all buyers with index $i < B$ trade at price p_B^b a volume equal to $v_i^b \frac{V_S}{V_B}$; else if $V_S \geq V_B$, then all buyers with index $i < B$ trade their volume v_i^b at price p_B^b, while all sellers with index $j < S$ will trade at price p_S^a a volume equal to $v_j^a \frac{V_B}{V_S}$. This is as efficient as in [18], but is fairer on the individual attributions, from which the burden $|V_B - V_S|$ is subtracted proportionally to the offer rather than uniformly.

4.1 Price incentives

In addition to the extra FIT reward proposed in Section 2.2[13], a dynamic incentive needs to be considered to synchronize battery charging with locally available renewable power. We propose the form of the incentive to be a rebate on the distribution/transport fee for those who buy electricity from the local market, as every wh exchanged through the market is assumed not to traverse the transformer. We propose the value to be proportional to the day-ahead forecast of the average renewable energy production of a house on the neighborhood. Let r^m be the maximum rebate considered, $p^u = p_1^u, ..., p_T^u$ to be the utility prices for the day, and $\hat{g}^n = \hat{g}_1^n, ..., \hat{g}_T^n$ be the forecast for the average renewable production, where the values are normalized so that $\hat{g}_t^n \leq 1 \ \forall t$. Then the minimum reservation price for each house at time slot t would be $p_t^r = p_t^u - \hat{g}_t^n r^m$ rather than p_t^u, which means that houses can potentially win more by making bids to charge their batteries when there is more renewable energy available.

[12] Auctions where offers are received from both buyer and seller side for multiple units of an asset.
[13] The analysis and simulations do not consider the extra FIT incentive.

5 Households optimization problem

We consider a hierarchical architecture where the control on the distribution grid level, based on market mechanisms as explained above, can be designed independently from the control mechanisms inside the households, which is a benefit with respect to more tightly coupled models such as bi-level optimization [68]. For illustrating the feasibility of our approach[14], a simple model of the problems that need to be solved by the HEMS is described. For the purpose of this article we consider a deterministic scenario in which consumption and production curves are known in advance[15]. This simplifying assumption relies on the capacity of batteries to absorb forecasting errors, particularly if forecasts were zero mean biased, and on the possibility of establishing similar market mechanisms closer to real time.

5.1 Determine offer quantities

Let $h \in \mathcal{H} = \{0, ..., 23\}$ denote the next hour for which the local renewable energy market will accept offers. The HEMS needs to find optimal offer quantities $\hat{v}^o_{t_0+1}, ..., \hat{v}^o_{t_0+6}$, where $t_0 = 6h$ is the base time slot of the hour h for 6 time slots per hour. The energy units to offer on the market depend on the optimal use of the battery. The amount of energy stored on the battery at the end of the time slot t is represented by e_t and its evolution in time is given by $e_t = e_{t-1} - s_t$, where s_t represents the amount of energy charged or discharged to/from the battery during time slot t. We require batteries to regain the initial state of charge at the end of the period $e_T = e_0$, so as to each study be independent, and also not to exceed one entire charge/discharge cycle of maximum 80% depth of discharge per day, to extend battery lifespan.

To satisfy such battery constraints, the HEMS needs to optimize over a rolling window formed by time slots $t \in \mathcal{T}_h = \{t_0 + 1, .., 144\}$, with $\tau_h = |\mathcal{T}_h|$. Each household has a (perfect) forecast of consumption $\ell_{h,t}$ and production $g_{h,t}$ for the rest of the day, from which it determines the gap $d_{h,t} = \ell_{h,t} - g_{h,t}$ that needs to be obtained by charging/discharging the battery or buying/selling on the local market. Households have the incentive to offer on the local market all the energy that is not exchanged with the battery, as they pay at most their bid limit price $p^b_{h,t}$ when buying and receive at least their ask limit price $p^a_{h,t}$ when selling.

Then, each household will look at the rest of the day and determine the best way of using the battery in order to minimize the electricity bill, depending on their limit prices and assuming that all the offers will be accepted. For each hour h the HEMS will solve the following linear program:

$$\arg\min_{x_h} a_h^T x_h \qquad a_h \in \mathbb{R}^{3\tau_h}, \qquad x_h \in \mathbb{R}^{3\tau_h} \tag{4.4a}$$

s.t.

$$x_{1,t} + x_{2,t} + x_{3,t} = d_{h,t} \qquad \forall\, t \in \mathcal{T}_h \tag{4.4b}$$

$$e_{h0} - \overline{E} \leq -\sum_{j=t_0+1}^{j=t} x_{3,j} \leq e_{h0} - \underline{E} \qquad \forall\, t \in \mathcal{T}_h \tag{4.4c}$$

$$-C^u \leq x_{1,t} \leq 0 \qquad \forall\, t \in \mathcal{T}_h \tag{4.4d}$$

$$0 \leq x_{2,t} \leq C^u \qquad \forall\, t \in \mathcal{T}_h \tag{4.4e}$$

$$|x_{3,t}| \leq C^s \qquad \forall\, t \in \mathcal{T}_h \tag{4.4f}$$

where e_{h0} is the accumulated energy on the battery up to hour h, the values $\underline{E}^i$ and $\overline{E}^i$ usually correspond to a SoC between 20% and 80% of the total battery capacity and C^u and C^s are the maximum

[14] For a business model analysis (out of the scope of this work) see [47].

[15] We do not address any particular forecasting mechanism/technology.

power that can be exchanged on one time slot with the grid and with the battery respectively. Variables $x_{h,t} = (x_{1,t}, x_{2,t}, x_{3,t})^T$ and deterministic coefficients $a_{h,t} = (a_{1,t}, a_{2,t}, a_{3,t})^T$ are as follows:

$$x_{1,t} : \hat{v}^a_{h,t} \quad \text{Energy to sell on local market} \tag{4.5a}$$
$$a_{1,t} = \begin{cases} p^a_{h,t}, & \text{if } g_{h,t} > \ell_{h,t}, \\ 0, & \text{else,} \end{cases}$$
$$x_{2,t} : \hat{v}^b_{h,t} \quad \text{Energy to buy on local market} \tag{4.5b}$$
$$a_{2,t} = p^b_{h,t}$$
$$x_{3,t} : s_{h,t} \quad \text{Energy flow with the battery} \tag{4.5c}$$
$$a_{3,t} = 0$$

With the solution we obtain the vector of offers $\hat{v}^o_h = \hat{v}^a_h + \hat{v}^b_h$ from which only the first 6 values corresponding to the next hour will be sent to the trading agent.

5.2 Determine final flows

Once the market results for each time slot of the next hour h are obtained by the trading agent, the HEMS needs to re-run the optimization problem in order to obtain the desired set point for the battery, as well as the flows to exchange with the utility, i.e.: the energy that is not exchanged with the battery will be sold for the FIT or bought from the supplier. The structure of the optimization problem is the same, except that the finally traded quantities $v^o_h = v^a_h + v^b_h$ are taken as an input and define the new gap to be satisfied $d_{h,t} = \ell_{h,t} - g_{h,t} - v^o_{h,t}$, and the optimization variables and parameters are as follows:

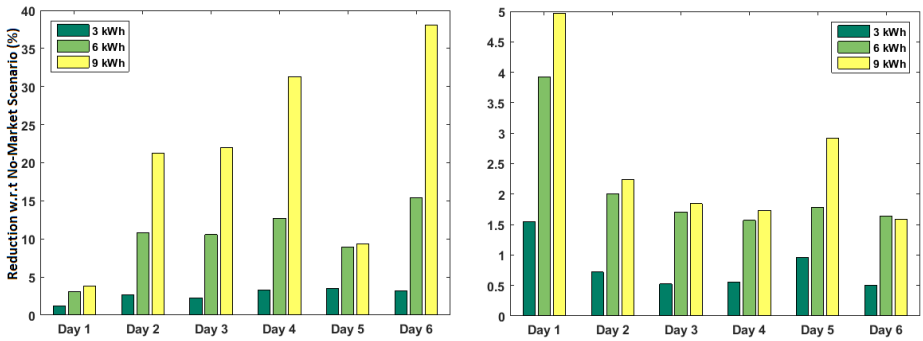
$$x_{1,t} : g^{FIT}_{h,t} \quad \text{Energy to sell for the FIT} \tag{4.6a}$$
$$a_{1,t} = \begin{cases} FIT, & \text{if } g_{h,t} > \ell_{h,t}, \\ 0, & \text{else,} \end{cases}$$
$$x_{2,t} : \ell^u_{h,t} \quad \text{Energy to buy from supplier } u \tag{4.6b}$$
$$a_{2,t} = p^u_{h,t} \quad \text{Price offered by supplier } u$$
$$x_{3,t} : s_{h,t} \quad \text{Energy flow with the battery} \tag{4.6c}$$
$$a_{3,t} = 0$$

6 Simulations and Results

6.1 Simulation tools, procedure and assumptions

We use power flow analysis as the means to assess the impact of the exchange of energy among households on quality of supply over the distribution grid. We rely on the Distribution Network Simulation Platform (DisNetSimPl) developed by EDF R&D. The platform provides an interface to several simulation tools, from which we use the open source Distribution System Simulator OpenDSS[16]. For

[16] http://smartgrid.epri.com/SimulationTool.aspx



(a) Energy out. (b) Energy in.

Figure 4.2 – Reduction of energy passing through the transformer.

illustrative purposes we designed an electricity network model conformed by a 20 kV/410 V transformer of 160 kVA rated power, two feeders with aluminum power lines of 240 mm^2 and neutral of 95 mm^2, following general specifications for French distribution grids[17][18]. The experiments were based on realistic synthetic consumption data obtained from the Multi-agent Simulator of Human Behavior SMACH [25]. The load curves correspond to 6 winter days of consumption from 33 households of mixed profiles. We requested data for intervals of 10 minutes in order to be able to simulate the system we define in Section 2.1.

The daily load served as an input to the individual household control mechanism; more precisely as the consumption forecast of each household. After each intraday decision taken and the corresponding market interactions, the flows to be exchanged with the battery and to be transacted with the neighbors are calculated. The final load curve exchanged with the grid for each household is used as an input for the DisNetSimPl simulator to analyze the impact of the market on the distribution grid.

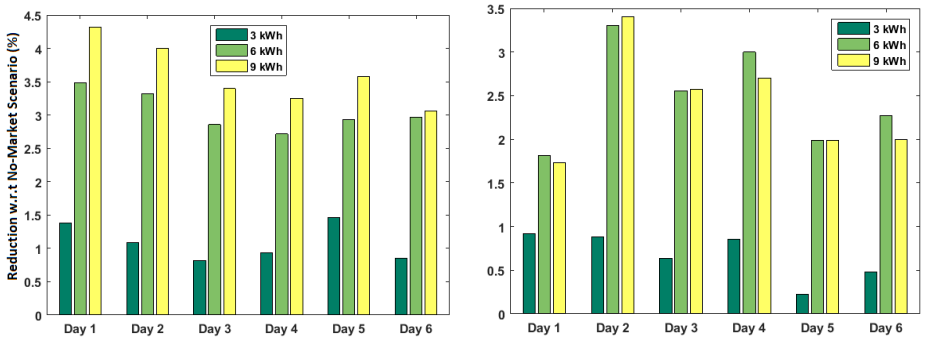
For the simulations we considered $N = 33$ households, 8 without flexibility (approx $N/4$), 8 with battery only (approx $N/4$) and 17 with PV panels and battery (approx $N/2$). We consider ideal batteries (without losses) of sizes, 3, 6 and 9 kWh. We consider a common supplier offering a Time Of Use pricing with two levels: 15 c€/kWh from 12 am to 4 pm and 45 c€/kWh from 5 pm to 11 pm[19]. The reserve prices of houses are randomly obtained from a uniform distribution with values ranging from 0 to 30% improvement over alternative prices from the utility, while the price rebate is below 2 c€/kWh.

6.2 Results and discussion

Results are presented as the percentage enhancement on the metrics introduced in Section 3 with respect to the scenario without market[20]. The results are shown for 6 days (where the only change on the simulation are the base load curves on every household) and for several battery sizes. For each simulation batteries in all households have the same size.

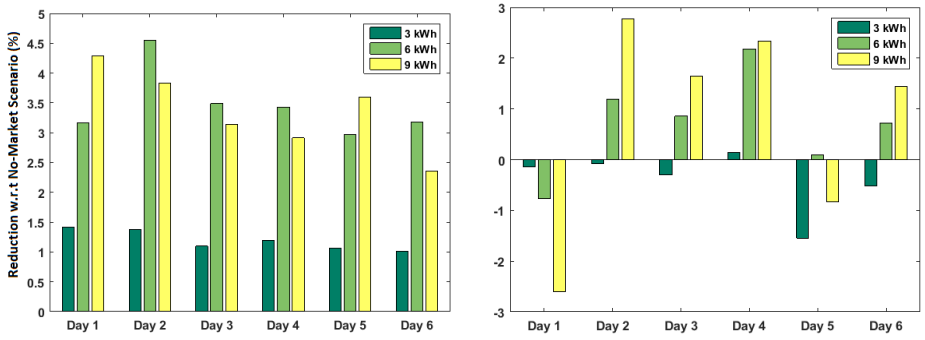
Figure 4.2a shows that a market enabling the exchange of energy among households coupled with appropriate incentives enables considerable reductions on the excess of renewable energy production towards MV. The non-decreasing dependency with the size of the battery is coherent with the increase in flexibility available for households, and it is maintained despite variations on residential demand

[17] http://www.enedis.fr/sites/default/files/Enedis-PRO-RES_43E.pdf
[18] Network file available at https://github.com/joluHo/P2P-energy-trading
[19] The usual peak price at midday does not fit the context of this work.
[20] Results are also applicable to centralized auctioneer implementations.



(a) Transformer losses. (b) Line losses.

Figure 4.3 – Reduction of losses.



(a) Loss reduction on phases. (b) Loss reduction on neutral.

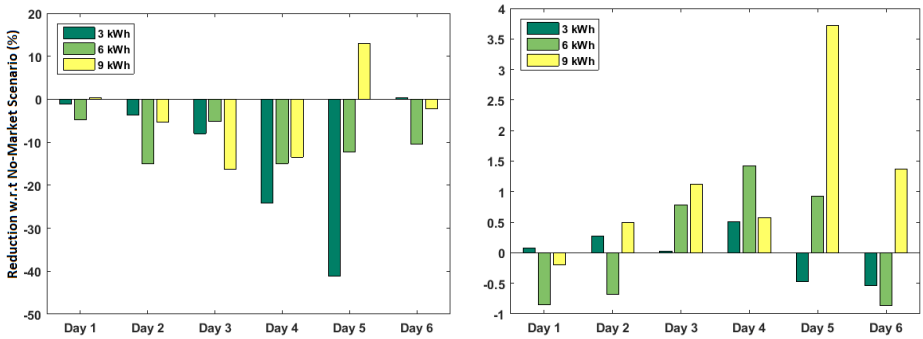
Figure 4.4 – Reduction of line losses.

in different days, with a lower impact on days 1 and 5 due to a lower aggregated demand on the peak hours. For the understanding of the behavior of the system it is interesting to note that, as the size of batteries increase, the excess of energy in houses with PV panels is reduced and the offers to sell on the market as well. This can also be explained by the fact that when the units per bid is increased and the units per asks is decreased, the amount of bidders participating on the market can potentially be reduced, creating a negative impact on the efficiency of the strategy proof market mechanism.

There is also a consistent reduction on the energy entering the transformer from the MV, though the reduction is less considerable as it represents a small share of the total demand. The total reduction of flow through the transformer leads to a reduction on transformer losses close to 4% for 6 and 9 kWh batteries, as we can see on Figure 4.3a. The total line losses are also reduced as shown in Figure 4.3b.

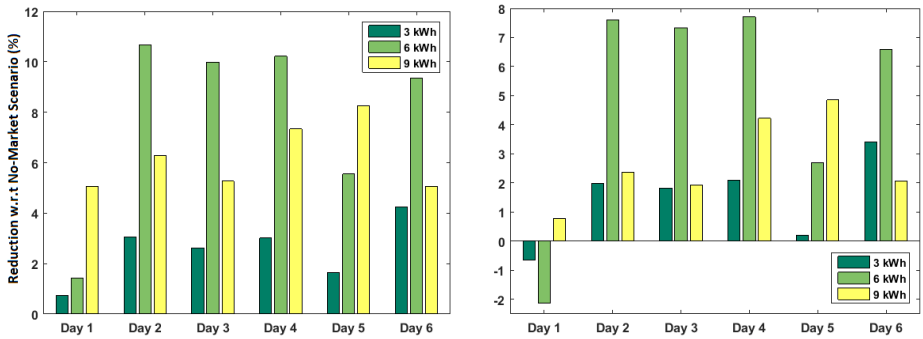
We can see, in Figure 4.4a, that the market consistently achieves a reduction of losses in line phases. This is not the case for the neutral as shown in Figure 4.4b. The market mechanism does not take into account the phases when allocating the quantities to be traded, leading to production on one phase being balanced with consumption in another phase. These unequal flows on the phases unbalance the network provoking an increase on the neutral current and respective losses.

The unbalance effect of the market is reflected by an important increase on the maximum VUF as shown in Figure 4.5. From the overall results of our analysis it is understood that the only negative impact of such imbalance would be on triphasic loads connected to the network. We are working on new market designs to cope with this issue.



(a) Maximum VUF. (b) Mean VUF.

Figure 4.5 – Voltage Unbalance Factor.



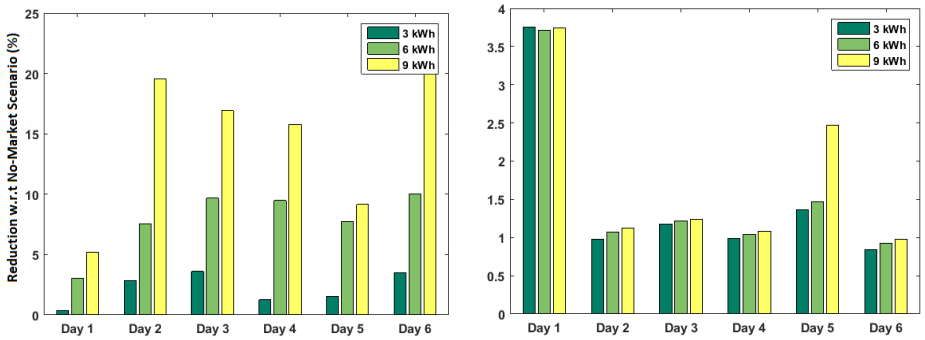
(a) Maximum transformer load. (b) Peak to Average Ratio.

Figure 4.6 – Grid congestion assessment.

Figure 4.6a shows that the peak load supported by the transformer is consistently and considerably reduced. The PAR is in some cases increased, due to a more important reduction on the mean load, which is also positive for the grid.

In current distribution networks voltage deviations depend on how loads are connected to the different phases and varies on time due to the load evolution of the different households. We observe that our system for some phases has positive impacts on voltage deviation, as shown in Figures 4.7a and 4.7b, but simultaneously in other phase the impact can be negative. Nevertheless, in all cases the operation limits are respected. Control on individual line current limits or voltage deviations require additional mechanisms that are considered in the following chapters, particularly in Chapter 6.

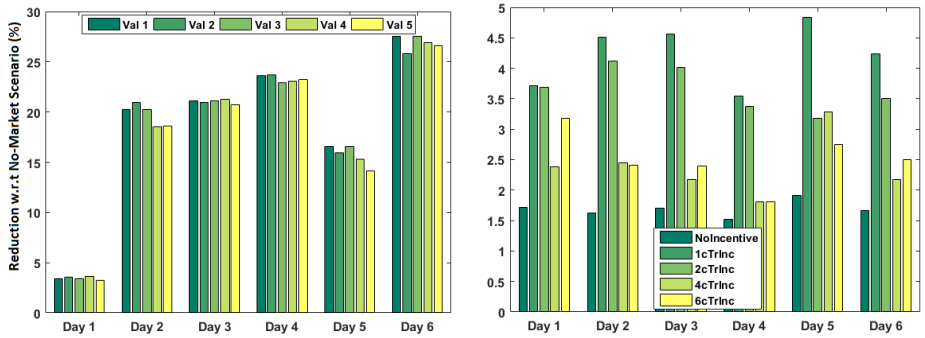
In the following we analyze the impact of distribution fee rebates and prosumer energy valuations. The simulations show that results are maintained for different random realizations for the valuations of prosumers over the energy they exchange on the renewable energy market; in particular, Figure 4.8a shows similar reductions on the excess of energy towards MV for different valuations. With respect to distribution fee rebates, the simulation results confirm the importance of incentives for synchronizing demand with renewable energy availability. The results obtained when providing incentives are consistently better when compared to the case without distribution fee rebates; in Figure 4.8b we can appreciate the reduction on transformer losses for values of maximum rebates equal to 1, 2, 4 and 6 c€ /kWh. From this figure we can also observe that finding the optimal incentive requires further analysis, as the relationship is not linear with variations in demand on different days.



(a) Maximum voltage deviation.

(b) Mean voltage deviation.

Figure 4.7 – Reduction of voltage profile deviation.



(a) Excess of energy towards MV under different valuations.

(b) Transformer losses under different price rebates.

Figure 4.8 – Impact of prosumer energy valuations and distribution fee rebates.

7 Conclusions and Perspectives

Major ongoing evolutions in the electricity industry, like local deployment of Renewable Energy Services (RES) and storage capacity, represent a key driver for the "energy transition" and related objectives. Nevertheless, the required transformations of the distribution grid are today delaying, and in some cases blocking, the possibility to leverage such opportunities. In this work we propose increasing RES hosting capacity by introducing autonomous markets for the exchange of energy among households aimed to locally balancing renewable energy production. The proposed system is based on auction mechanisms and dynamic transport fee rebates that serve as an incentive for households to control their energy resources in a way that benefits both prosumer and operator. The architecture relies on a blockchain-based transactive platform to enable the coordinated participation of any type of player, including DSOs, aggregators, and prosumers, thanks to its increased security, transparency and auditability with respect to centralized implementations.

To the best of our knowledge, our work is the first to propose a thorough assessment of the impact of the exchange of energy among households on distribution grid quality of supply, for which we use power flow simulations with realistic load data. The results show that the auction mechanism and price incentives proposed on this chapter enable an increase of RES hosting capacity by reducing the maximum power flowing through the transformer and reducing losses on both the transformer and the lines. Moreover, the fact of locally balancing the excess of Photovoltaic (PV) production reduces

the possible negative impacts of massive PV deployment on the global grid. Additional benefits could be obtained if the mechanisms could reduce voltage deviation and network unbalance. An approach for coping with these issues could be enabling Distribution System Operators to actively provide incentives and constraints for the operation of Distributed Energy Resources. Analyzing the impact of forecast uncertainty on the obtained results is a relevant subject for future work.

Chapter 5

Augmenting DER hosting capacity of distribution grids through local energy markets and dynamic phase switching

1 Introduction

Distributed Renewable Energy Sources (RES) are one of the main enablers for the energy transition and currently one of the highest growing industries worldwide [77]. Nevertheless, their potential is being hindered by the limited capacity of distribution grids for hosting renewable energy, due to their negative impacts on quality of supply, in terms of peak flows, voltage deviations and network unbalance[1].

Local energy markets have been recently introduced as a solution for the integration of the increasing number of PhotoVoltaic (PV) panels being deployed at residential premises. These markets, as discussed in Chapter 4, can schedule renewable energy flows and flexible demand (from batteries or controllable loads) in a way that benefits prosumers[2], other market players and Distribution System Operator (DSO)s, in particular, reducing average and peak flows through the transformer, as well as transformer and line losses.

However, as most existing ex-ante demand side management mechanisms, the schedule of Distributed Energy Resources (DER)[3] provided by the proposed local markets, does not take into account the phases to which households are connected to; thus, the excess of production in one phase can be balanced with flexible demand on another phase, creating further uneven distribution of flows across phases. Such a degradation of network unbalance favors larger voltage rises/drops and has a negative impact on line losses[4]. Furthermore, it strongly affects three-phase loads such as motors, drastically reducing their lifespan. For these reasons the DSO must maintain the Voltage Unbalance Factor[5] under 2% as one of the main quality of supply metrics.

The purpose of this chapter is to propose and evaluate mechanisms for enabling to benefit from all the advantages from local markets without suffering from the mentioned network unbalance issues.

[1] Refers to the uneven distribution of flows across phases. Also called Voltage unbalance.
[2] Consumer evolution towards pro-active participation on grid activities.
[3] Flexible loads, controllable generation and storage resources.
[4] An imbalanced distribution line may yield up to three times more power losses compared to a balanced one [19].
[5] A commonly used metric for measuring network unbalance, which was introduced in Chapter 4.

To reach this objective we propose to combine local markets with Dynamic Phase Switching. In particular, we propose cost effective mechanisms for the selection of households to be switched and for their optimal allocation to phases. Every time the local market decides on the flows to be exchanged among households, the phases are reallocated accordingly with the aim to minimize the Voltage Unbalance Factor (VUF). The solution is based on Solid-state Transfer Switches (STS) installed at the Point of Common Coupling (PCC) of some of the market participants.

We analyze the performance of the proposed mechanisms based on power flow analysis and realistic load curves. The results show that the deployment of STS on only 6% of households is enough to achieve the objectives mentioned above. Furthermore, only 12% of them are enough to reach a quality of supply similar to the one observed on a setting without connected renewable energy sources.

The chapter is organized as follows. First, in Section 2, we introduce the system under study. In Section 3, we discuss related work on dynamic phase allocation. Then, in Section 4, we introduce our model for selecting households to switch and for their allocation to phases, and in Section 5, we provide a comprehensive analysis of the aggregated impact of markets and Dynamic Phase Switching (DPS) on distribution grid quality of supply. Finally, we conclude the chapter and share some perspectives.

2 System description

The low voltage distribution grid under study consists of one Medium Voltage (MV)/Low Voltage (LV) transformer and one or more three-phase four-conductors feeders to which households are connected. We consider four types of households: with a PV panel and a battery, with a battery but without PV, with PV but without battery, and without battery or PV, but with flexibility from controllable loads; all types of houses are equipped with smart meters. We assume the flows from the PV panel and to/from the battery can be controlled by means of smart inverters [75]. This enables households to control the destination of the excess of renewable energy as well as the source of the energy that satisfies load demands. Such control over flows enables households to exchange energy and services through local markets, as described in Chapter 4.

Local markets, as we previously mentioned, can degrade the VUF of distribution grids. The solution proposed in this chapter is to combine local energy markets with DPS, as will be introduced in Section 2.2. The solution is based on STS that are described in Section 2.3[6].

2.1 Local energy market

We focus on the the market proposed in Chapter 4, which is aimed to balancing renewable energy with flexible demand. This market provides hour-ahead commitments from participating households about their expected flows to be exchanged with the grid during 10-minute time slots.

The market needs households to enforce their commitments even in the presence of uncertainty on their private forecasts from which they obtain their control decisions. For this, it includes economic incentives for households to absorb their forecasting errors in real-time by controlling their battery or flexible loads accordingly. In addition, the market implementation over a blockchain-based transactive platform (See Chapter 4) provides fine-grained visibility to the DSO over household commitments, wich will be exploited for better balancing the grid. In this chapter we assume that market commitments are perfectly enforced. We are aware that forecasts may deviate considerably and that it may be difficult to completely absorb the error with demand flexibility, in which case the performance

[6]The two main differences with the system analyzed in Chapter 4, are the STS and an additional type of house (with PV panel but without battery).

of DPS may be degraded. Nevertheless, a sensibility analysis and eventually a stochastic approach are to be part of future work.

2.2 Dynamic Phase switching

Network unbalance is a general problem in LV residential distribution grids. Most LV loads are single-phase loads. Even for houses that are three-phase connected to the grid, unbalance occurs since a large part of their loads are still single-phase. The traditional solution is to reallocate the phases of some single-phase customers based on their average load profiles over long time periods. This requires a technician to manually switch phase connections, implying high costs and no adaptability. For these reasons, such a static approach is only applied when the distribution grid reaches voltage drop/rise limits or when the VUF is close to 2%.

The aim of DPS is to counteract the negative effect of scheduling mechanisms and to augment the hosting capability of the grid, rather than reallocating phases only when quality of supply reaches critical values. Whenever the DSO detects that VUF, peak voltage rise/drop or neutral losses are above typical values (values observed before local markets and DER deployment), a set of households on the corresponding feeder could be selected for installing a phase transfer switch following the mechanisms proposed in Section 4.2. Thus, the deployment of STS can be done progressively depending on the needs of each distribution grid. The model we propose can be used to determine the amount of switches to be deployed, by simulating with an increasing number of switches until the desired quality of supply is achieved. In Section 5 we show that only a small set of STS will be enough to maintain an acceptable quality of supply even in a scenario with 80% of households equipped with PV panels and 60% with storage.

The operation of the switches will be as follows. For every time slot, the corresponding market results and the current allocation of phases are taken into account[7] for the selection of the new allocation, following the mechanisms described in Section 4. We consider a 10-minute time scope, as well as the market, based on constraints imposed by regulation on voltage deviations over that period of time [16], which can eventually lead to the temporary disconnection of PV panels [17]. The new allocation is communicated to the corresponding phase switches shortly before the beginning of the the period, to account for communication delays.

2.3 Solid-state Transfer Switches

The proposed implementation for the transfer switches is composed of three Si-IGBT[8], one for each phase, three mechanical contactors and a controller. A logic interlock needs to be implemented to avoid short-circuits among phases, meaning that only one switch/contactor is closed at any given time, while the other two remain open. Once a switching order gets to the controller, it will first allow the switch to take over the active connection from the contactor, then it will break the current switch connection and make the new connection with the corresponding switch, after which the contactor of the new phase connection will take over the switch. The switches are chosen by their capability to work at high frequencies (200 Hz). It allows that the time during which loads are not fed when performing break-before-make operations is reduced to a safe minimum, which in this case could be around 5 ms. In [20] it is shown by simulation that the impact of such interruptions on the Rooth Mean Square values perceived by loads respects the quality of supply requirements imposed to the DSO, since they last for less than a quarter of a cycle. These design decisions ensure that loads

[7] Note that STS would have access to local voltage measurements, which could be exploited in future work to obtain improved results using more complex mechanisms.

[8] Interlocked Insulated-gate Bipolar Transistor switches, extensively used in PV and battery inverters. Sic-MOSFET can also be used [78]

will not be affected by the switching operations, short-circuits are avoided thanks to the interlocking and switches are protected from faults by relying on standard mechanical contactors.

The control signals are sent through the advanced metering infrastructure and then relied to the STS by their corresponding TIC [21] or BlueTic [22]. This could be done in France as in a considerable share of households the meter is installed close enough of the connection box where the phase gets selected. Furthermore, Bluetooth technology would simplify monitoring and maintenance for operators, that could obtain information and control the STS without even opening the box.

3 Related Work

We previously mentioned that most scheduling mechanisms do not take into account the phase to which households are connected to. An example of mechanisms that do consider phase allocations are those based on Unbalanced Three-Phase Optimal Power Flow [23]. Nevertheless, these require complex computation, detailed knowledge on the structure of the grid and do not consider DPS explicitly. In this section we analyze the previous proposals for DPS.

Most of previous DPS proposals [19,24] do not consider renewable energies, which have a major impact on grid unbalance and voltage deviations. In particular they have an impact on the variability of conditions that make existing studies too coarse-grained (at most one hour granularity) to cope with voltage constraints (10 minutes).

In [24] they propose a decentralized method for switching phases in order to minimize the deviation from the average current on the phases, based on local current measurements and three-phase switches installed in some of the nodes of the grid. They also propose a genetic algorithm aimed to find the minimum number of switches that need to be installed and their location in order to minimize feeder losses. It's the only article taking into account location of loads. Nevertheless, their approach requires measurements of aggregated currents on every branch where a switch is connected, and the decentralized decision making process requires coordination without communication, which is supposedly achieved by synchronizing the execution of the algorithm at predefined intervals from the terminal loads of each feeder back to the transformer.

In [20] they propose a centralized load transfer scheme to dynamically minimize voltage unbalance. The method relies on end-user controllers and three-phase switches installed at each house sending consumption information every 15 minutes. They propose a sequential process over the buses for the selection of load transfers from the highest-loaded to the least-loaded phase, relying on load flow studies to determine the load transfer resulting in the lowest voltage unbalance along the feeder, which is complex and requires detailed knowledge of the grid structure. Additionally, they propose a genetic algorithm for achieving a voltage unbalance closer to the optimal. The size of loads/injections to be transfered is not considered and simulations are provided for a single feeder with only one household per bus/PCC and per phase.

The mechanisms proposed in the literature require households to periodically share information on the flows exchanged with the grid, even though the phase to which they are connected has no impact for them and thus they have no incentive to share truthful information. It is well known that in a scenario where rational agents need to provide private information, some kind of incentive must be provided for the agents to reveal part of this information. In our work a local energy exchange market provides the incentives for households to reveal the information and to do it truthfully. Furthermore, existing mechanisms rely on complex algorithms in charge of an extensive search over all possible phase switches. Instead, we believe the most appropriate question is to find simple algorithms that would achieve considerable reductions of voltage unbalance with a reduced set of phase switches and with minimal requirements of information.

4 Dynamic Phase Switch Model

4.1 Phase allocation

Let $\mathcal{H}$ denote the set of H households on a low voltage distribution grid, from which a subset $\mathcal{M}$ of M households participates on the local energy market. The houses in $\mathcal{M}$ are eligible for installing STS as part of the set $\mathcal{E} \subset \mathcal{M} \subset \mathcal{H}$ of size E. Let denote the houses with static phases by $\mathcal{N}$ of size $N = H - E$. A phase allocation can be seen as a bipartite graph formed by the set of households and the set of phases as shown in Figure 5.1, where the matrix element $x_{i,j}$ is 1 if the household j is connected to the phase i, and 0 otherwise. The graph is semi-regular on the set of households with degree 1, as a house can be connected only to one of the three phases. From now on, we are going to work only with the boolean adjacency matrix $X \in \mathbb{B}^{3\times H}$ of the graph.

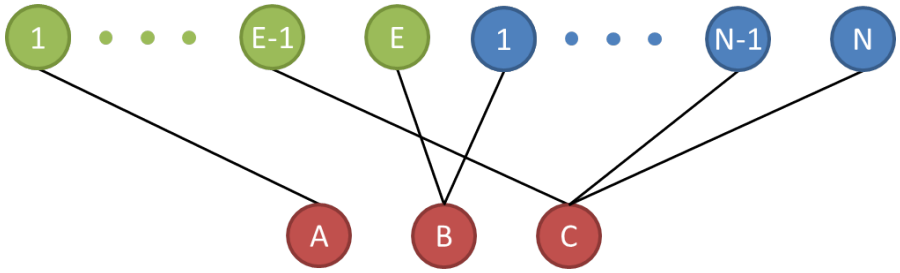


Figure 5.1 – Phase assignment graph.

4.2 Choice of households to switch

For the dynamic approach we have to decide first, beforehand, in which set of households $\mathcal{E}$ to install STS and then how to operate them in order to minimize network unbalance. In this section we propose simple heuristics to choose the households where to install STS. We propose mechanisms that rely only on information that is already available to a DSO, without additional requirements on measurement or communications equipment. We assume the DSOSO has access to the average flows exchanged by households with the grid and also to aggregated voltage unbalance measurements.

4.2.1 Mean-based selection mechanism

In this case the houses in which switches will be installed are those for which a DSO running a static phase allocation would decide to switch phases. Therefore, the decision is based on average loads on the long run.

4.2.2 Highest Average Flow selection mechanism

We first pre-select houses with PV panels that are currently assigned to the phase with the highest average voltage and households without PV panels that are assigned to other phases, preferably the one with the lowest average voltage. This allows to reduce production on the highest average voltage phase and/or to reduce consumption on the lowest average voltage phase. Then, among the pre-selected households, we choose the one/s with the highest average flow (injection and demand respectively), in order to maximize the impact of each switch and limit to a minimum the number of phase transfers required to balance flows across phases.

This strategy is useful for the initial switch deployments, but it can be refined for better fitting the voltage unbalance gap and to further improve the performance of the system. This is a subject of future research in which machine learning can be exploited for finding the optimal houses where to install phase switches depending on flow profiles and voltage unbalance data.

4.2.3 Hybrid

A hybrid approach is also possible, in which the Mean-based (MB) mechanism can be used for a pre-selection and then Highest Average Flow (HAF) selection would be applied to obtain the final set of candidates.

4.3 Dynamic phase allocation

The phase reallocation decision only[9] relies on market commitments made by houses rather than on specific measurements for the period in question. Thus, we propose to minimize the negative impact of market participants, which are in fact the ones that have the highest impact on voltage unbalance due to their DER.

Minimizing the impact of flows imposed by market participants on voltage unbalance requires those flows to be as balanced as possible across phases. Let e be the aggregate of commitments of market participants for the time slot on the corresponding feeder, we aim to obtain a phase allocation of the set of switches $\mathcal{E}$ such that the flow imposed by the set of market participants $\mathcal{M}$ on each phase is as close to the average $e_m = \frac{e}{3}$ as possible. For this, a natural metric to minimize is the least square distance of the corresponding flows. The binary vector $x = [x^a, x^b, x^c]^T \in \mathbb{B}^{3M}$ represents the phase allocation of market participants such that $X = [x^{aT}, x^{bT}, x^{cT}] \in \mathbb{B}^{M\times 3}$ is the corresponding adjacency matrix of the phase allocation graph. Then, the problem to be solved is

$$min_x ||\bar{e} - P^T x||^2 \tag{5.1}$$

s.t.

$$x^a + x^b + x^c = \mathbf{1} \tag{5.2}$$

$$x^0 x^T = N \tag{5.3}$$

$$x_i \in 0, 1, \forall i \in \{1, \ldots, 3M\} \tag{5.4}$$

Where $\bar{e} = [e_m, e_m, e_m]^T \in \mathbb{R}^3$, and $P \in \mathbb{R}^{3M\times 3}$ is a block diagonal matrix formed from the vector of prosumer commitments $p_c \in \mathbb{R}^M$, such that the product $P^T x$ denotes the vector of prosumer aggregated flows on the 3 phases for a given phase allocation x. The constraint (5.2) ensures only one allocation per house is given, where $\mathbf{1}$ denotes the ones vector of size M. The constraint on the Hamming distance between x^0 and x in (5.3) ensures that houses of the set $\mathcal{N}$ will keep their phase allocations, as x^0 represents the current phase allocation, but with zeros on the elements corresponding to $\mathcal{E}$.

This problem can be classified as Mixed Integer Least Squares (Mixed Integer Quadratic Program) and expressed as follows

$$\min_x x^T Q x + f^T x \tag{5.5}$$

s.t.

(5.2) − (5.4)

[9] In addition to market results, the DSO needs the list of households per feeder and their current phase allocation (just like in the static case).

where Q and f can be expressed in function of the parameters of the original problem (5.1) as follows: $Q = P^T P$ and $f = -P\overline{e}^T$.

5 Simulations and Results

5.1 Procedure and system scenarios

The simulation procedure is organized in four parts. First, we select the households where to install the switches. Then, we simulate the local electricity market. For each outcome of the market we decide how to dynamically allocate households to phases. Finally, we rely on power flow analysis to assess the performance of the system, using the scenario without market as a base of comparison and the static approach as the benchmark[10].

The evaluation procedure has two parts. First, in Section 5.4.1, we evaluate the performance of dynamic vs. static phase switching. For this, we consider a scenario with massive deployment of DER and the same amount of phase switches for static and dynamic approaches. In this case, we consider $H = 33$ households, 8 without flexibility (approx $H/4$), 8 with battery only (approx $H/4$) and 17 with PV and battery (approx $H/2$). We consider that only households with batteries participate on the market.

Then, in Section 5.4.2, we evaluate the adaptability of both static and dynamic approaches as we evolve towards massive deployment of DER. In particular, we compare the amount of phase switches needed to achieve a reduction in maximum VUF and peak Voltage rise/drop, with respect to a scenario without scheduling. For this, we consider a set of four scenarios that would represent the progressive adoption of DER in a neighborhood composed of 50 households:

- Senario A (20% storage, 30% renewable) : 30 without DER, 5 PV + storage, 10 PV only, and 5 storage only.
- Senario B (40% storage, 40% renewable) : 20 without DER, 10 PV + storage, 10 PV only, and 10 storage only.
- Senario C (60% storage, 50% renewable) : 10 without DER, 15 PV + storage, 10 PV only, and 15 storage only.
- Senario D (60% storage, 80% renewable) : 5 without DER, 25 PV + storage, 15 PV only, and 5 storage only.

For illustrative purposes in Figure 5.2, we show the structure[11] of the distribution grid under study and the transition from scenario A to Scenario B in terms of adoption of DER.

In these progressive scenarios we consider all households participate on the market and are eligible for DPS. For the selection of households, we consider the hybrid mechanism introduced in Section 4.2.3. This allows us to compare dynamic and static approaches based on the same set of households.

5.2 Energy market simulation

For the local energy market simulation, we reproduce the procedures described in Chapter 4, where households minimize their electricity bill by solving a simple linear program that finds the optimal quantities of energy to offer on the market. Then, a Multi-unit double auction is implemented over a

[10] A comparison to other more complex approaches to dynamic phase allocation are out of the scope of this work.

[11] The structure is composed of a Voltage source representing the upstream electricity grid and the rest of components described in section 2. Despite cable segments are represented by similar sized components, in fact each segment has a different length.

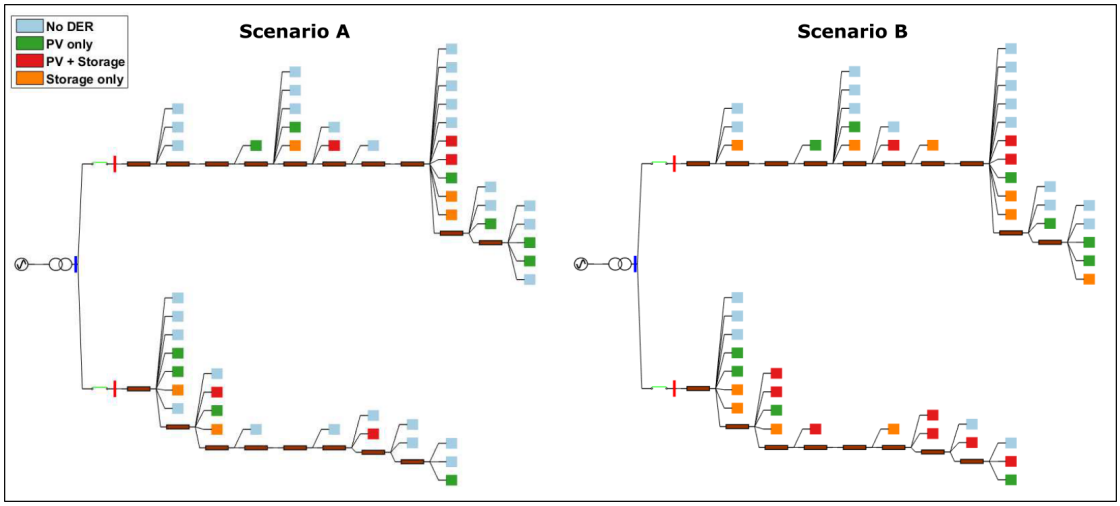


Figure 5.2 – Distribution of DER for Scenarios A and B.

test blockchain network [60] to establish the prices and quantities exchanged among households for every time slot. Once households receive the final quantities and prices, they optimize battery usage and send a new transaction for the flow to be exchanged with their electricity supplier.

5.3 Simulation tools and parameters

For the DPS mechanisms we use MATLAB [45] together with the Gurobi [46] optimization suite. For the power flow analysis; we rely on the Distribution Network Simulation Platform (DisNetSimPl) developed by EDF R&D, which provides an interface to several simulation tools, from which we use the open source distribution system simulator OpenDSS [79]. We use a slightly modified version of the electricity network model provided in Chapter 4, conformed by a 20 kV/410 V transformer of 160 kVA rated power, two feeders with aluminum power lines of 150 mm^2 and a neutral conductor of 70 mm^2.

The parameters used for the simulations where the following:

Load profiles - We use realistic synthetic consumption data obtained from the Multi-agent Simulator of Human Behavior SMACH [25] as input for the household optimization problem. The load curves correspond to 6 winter days of consumption on a 10-minute basis from 50 households of mixed profiles.

Production profiles - We consider the same synthetic production curve for all the PV panels (all located on the same area).

Batteries - We consider ideal batteries of 6 kWh capacity.

Electricity prices - We consider a common supplier offering a Time Of Use pricing with two levels: 15 c€/kWh from 12 am to 4 pm and 20 c€/kWh from 5 pm to 11 pm.

5.4 Results and discussion

We analyze the results in two steps. First, we compare the potential of dynamic and static phase switching to solve network unbalance issues. We compare the impact of both mechanisms for the same amount of phase switches. Then, we study the adaptability of both mechanisms to the increasing deployment of DER.

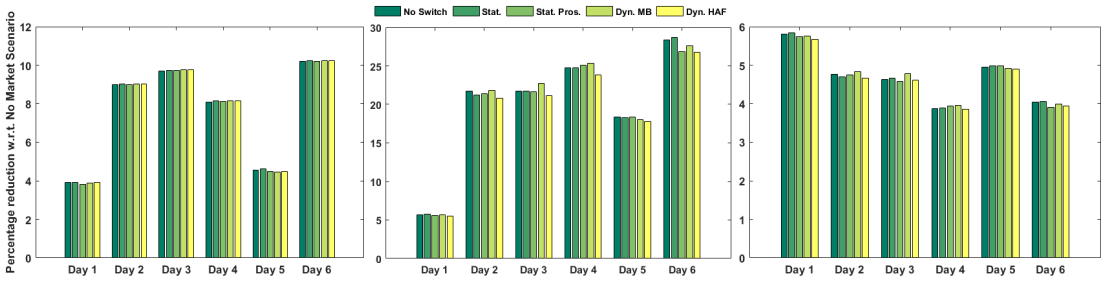
The different phase allocations considered are as follows

- **No Market -** Initial phase allocation.
- **Stat. -** The static approach (benchmark).
- **Stat. Pro. -** Static approach constrained to market prosumers.
- **Dyn. MB -** Dynamic approach with MB selection.
- **Dyn. HAF -** Dynamic approach with HAF selection.

5.4.1 Impact analysis

First, we analyze the impact of phase transfers on the benefits of local energy market interactions. For this we consider metrics related to energy passing through the transformer, the corresponding losses on the transformer and the reductions on peak load. The results are presented as the percentage enhancement of the corresponding metric with respect to the scenario without market. The results are shown for 6 days (where the only changes on the simulation from one day to the next are the base load curves on every household).

As expected, these metrics are barely impacted by phase switching, as all are aggregated measures of load and losses at the transformer level. In Figure 5.3a we present the effect on peak flows which is barely visible, while in Figures 5.3b and 5.3c we present the variations on the energy through the transformer and the corresponding losses respectively, which are visible but remain negligible. The benefits of local energy market are maintained for all phase switching mechanism tested.

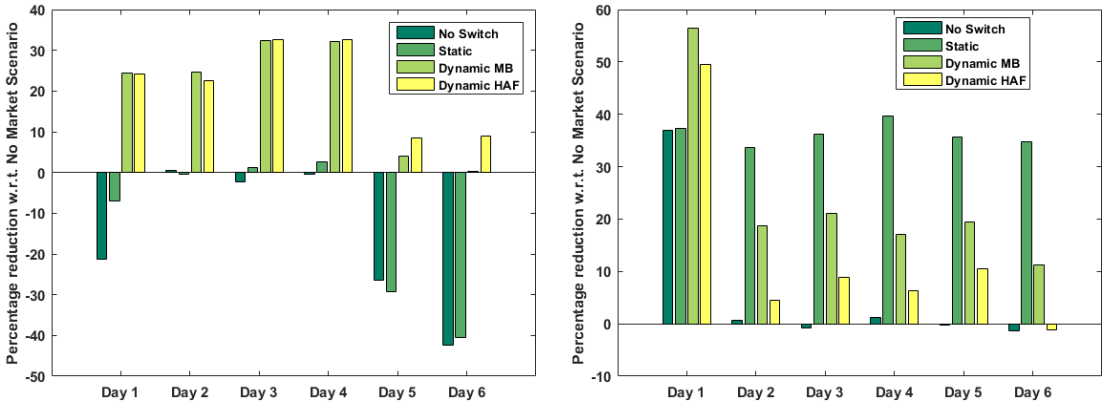


(a) Peak flows. (b) Energy out. (c) Transformer losses.

Figure 5.3 – Reductions on transformer load and respective losses.

Then, we analyze the performance of phase transfer mechanisms on reducing maximum VUF, peak voltage rise/drop and neutral losses. We compare static and dynamic approaches for a total of 4 phase switches (around 10% of households) in each case[12].

[12]For 20% of households (7 phase switches) the results are similar.



(a) Maximum VUF. (b) Mean VUF.

Figure 5.4 – Voltage Unbalance Factor reduction.

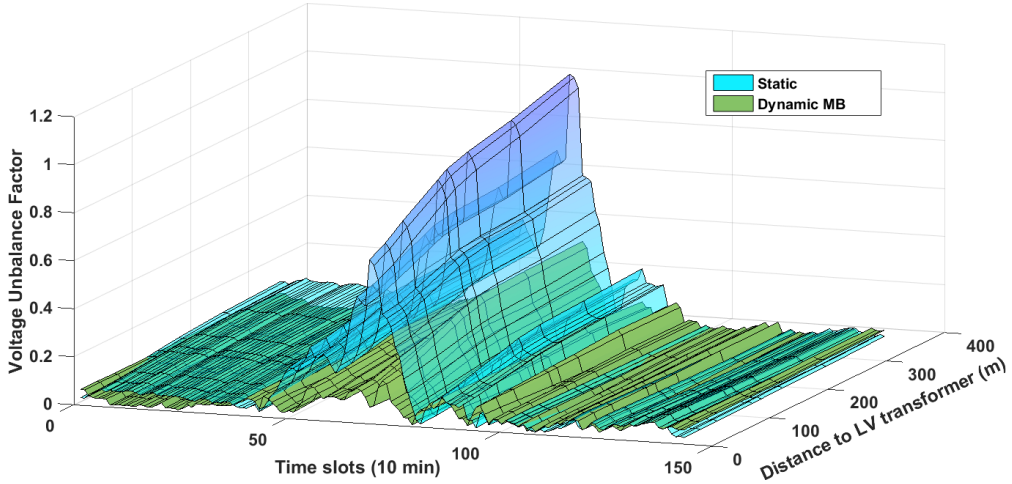
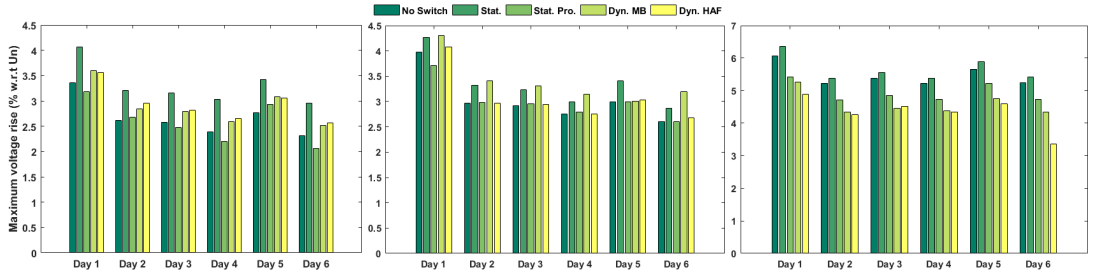


Figure 5.5 – VUF daily variation along the feeder for four Manual and Dynamic Phase switches.

As expected, the results in Figure 5.4b show that the current static approach is successful in achieving a reduction of mean VUF, but fails to achieve consistent reductions of the peak VUF in Figure 5.4a; while dynamic approaches perform much better for reducing peak VUF for the same amount of phase switches. A static approach would need more phase switches to achieve a reduction on peak VUF, because it strongly depends on the variability of flows imposed by DER and their allocation through scheduling mechanisms, rather than on average flows. For example if the house chosen to be switched by the static mechanism is scheduled for reducing injection or consumption during the peak VUF period, the static mechanism would fail, while the dynamic mechanism would adapt.

In order to illustrate the relevance of peak values of VUF in the presence of DER, in Figure 5.5 we show the variation of VUF values over time for Day 1 along the highest loaded feeder. The comparison is made for four phase switches, with 3 being made (resp. installed) in the highest loaded feeder, following the static and Dynamic MB selection approaches. The figure illustrates the strong influence of renewable production and phase switching on voltage unbalance, up to the point that a couple of households with installed PV panels connected to the highest loaded phase can heavily degrade the quality of electricity supply.



(a) Phase A. (b) Phase B. (c) Phase C.

Figure 5.6 – Maximum voltage rise on phases along any of both feeders.

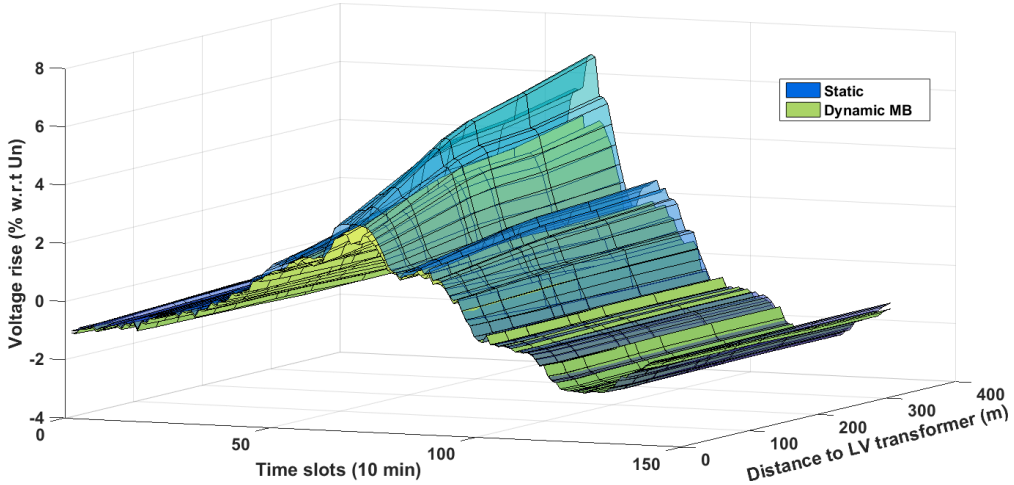
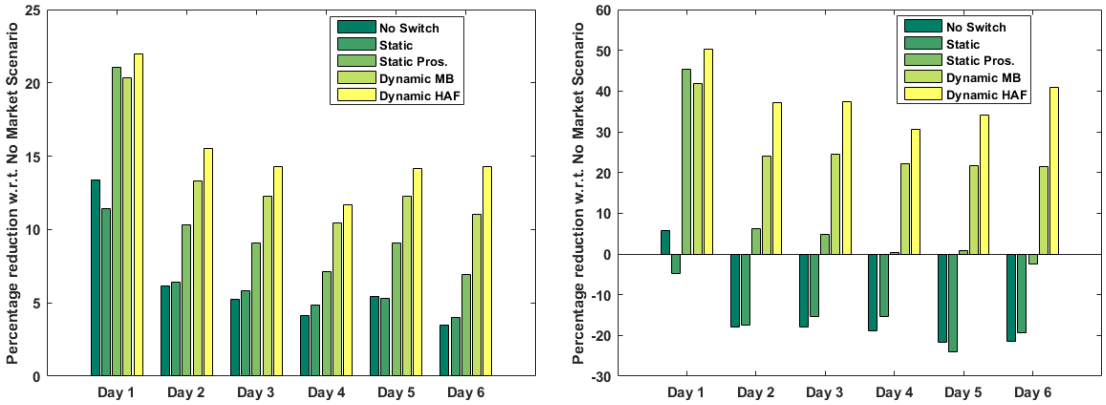


Figure 5.7 – Voltage drop/rise daily variation along the feeder for four Manual and Dynamic Phase switches.

With respect to voltage rise/drop reduction, the expected impact of a better balancing among phases would be a reduction on the difference in voltage between phases and thus a potential reduction of the maximum voltage rise/drop. In Figure 5.6 we can see the maximum voltage rise observed at each of the phases for different phase allocations. The phase C is the phase with higher voltage rise and we can see that DPS achieves reductions of around 15% and 20% with respect to the no-switching case for the MB and HAF selection approaches respectively; these results are in all cases better than the static approach, which in fact increases the highest voltage rise.

It is interesting to highlight that the static approach constrained to market participants performs much better than the general static approach for peak voltage rise/drop reduction while the opposite is observed (as expected) for peak and mean VUF reduction. This suggests that a combined choice of households to switch based on both objectives (peak VUF and peak voltage rise/drop reduction) could potentially provide better results for DPS.

Similarly to the VUF case, in Figure 5.7 we illustrate the variation of voltage on the highest-loaded phase during an entire day along the highest-loaded distribution feeder. We compare the Static constrained to prosumers and the Dynamic HAF phase switching mechanisms allowing for 4 phase switches. We observe a considerable reduction of the maximum voltage rise and similar variations with time and along the feeder in comparison to VUF in Figure 5.5.



(a) Loss reduction on phases.

(b) Loss reduction on neutral.

Figure 5.8 – Reduction of line losses.

Finally, we analyze the performance of phase switching with respect to losses, and in particular for neutral losses. In Figure 5.8 we can see how the market mechanism achieves a reduction of line losses but simultaneously increases neutral losses most of days. The static mechanism fails to solve the issue, while the dynamic mechanisms achieve a consistent and considerable reduction of both line and neutral losses.

5.4.2 Adaptability analysis

Next we analyze the adaptability of our DPS solution compared to static switching along scenarios that represent a possible development of a residential distribution grid in the years to come, as introduced in Section 5.2. First, we take a detailed view on the transition from scenario A to B. Then, we compare the amount of phase switches needed to achieve a reduction of peak VUF with respect to a scenario without market. Finally, we determine the amount of STS in order to achieve, in all cases, a superior performance with respect to both VUF and Voltage rise/drop. The amount of phase switches needed is an important metric due to the high costs of implementing/deploying each one of them.

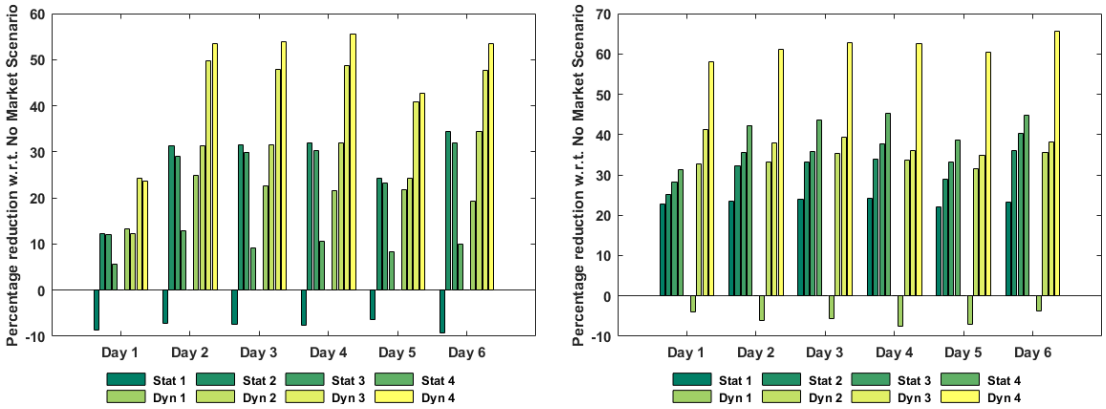
In Figures 5.9 and 5.10 we have the percentage reduction of maximum and mean VUF, with respect to the scenario without market, for scenarios A and B respectively. For the scenario A we see the impact of up to four phase switches for each of the mechanisms, while for the scenario B, we assume 2 static (resp. dynamic) phase switches were realized (resp. installed) during the period corresponding to scenario A[13], and up to 6 static phase transfers and no extra STS being installed during period B.

With respect to maximum VUF, we can see in Figures 5.9a and 5.10a, that with a total of 2 STS, installed for scenario A, we achieve maximum VUF reductions of over 20% in both scenarios, while the static approach needs 8 phase switches to attain a satisfactory performance (2 during scenario A and 6 in B).

With respect to mean VUF, the results for scenario A show, as expected, that increasing the number of phase transfers further reduces the mean VUF (Figure 5.9b), but not necessarily the maximum VUF (Figure 5.9a), as seen in the previous section. Nevertheless, for scenario B this is clearly not the case; as we can observe in Figure 5.10b, the impact on mean VUF gets degraded in several cases when performing additional static phase transfers.

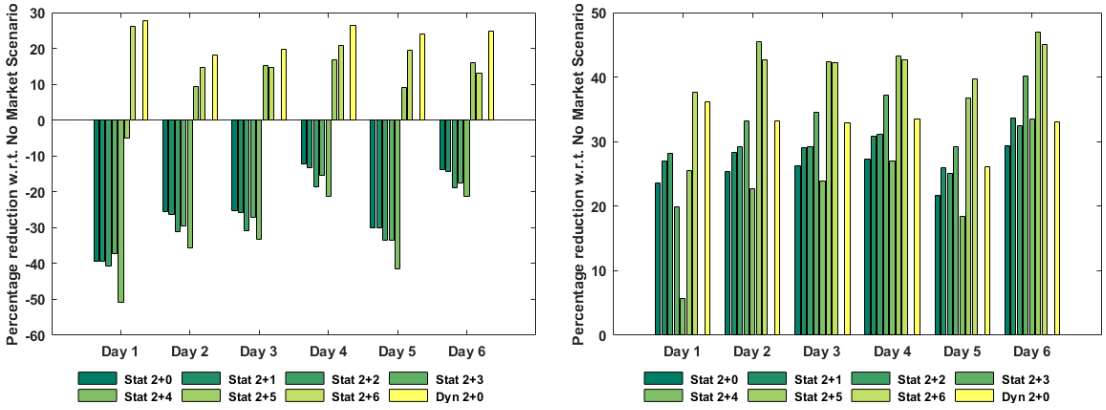
The unexpected rise on VUF happens despite the weekly average load in both feeders becoming effectively better-balanced across phases as we perform additional static phase transfers. This can be

[13] the notation 2+x on Figure 5.10 represents 2 switches during period A and x switches during period B



(a) Reduction on maximum VUF. (b) Reduction on mean VUF.

Figure 5.9 – Reduction of VUF for Scenario A.



(a) Reduction on maximum VUF. (b) Reduction on mean VUF.

Figure 5.10 – Reduction of VUF for Scenario B.

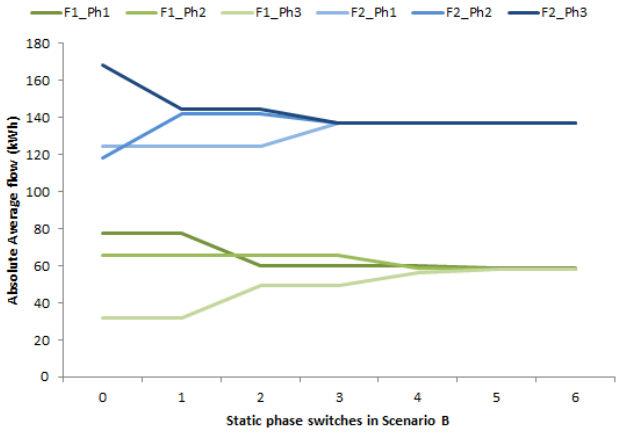


Figure 5.11 – Voltage drop/rise daily variation along the feeder for four Manual and Dynamic Phase switches.

appreciated in Figure 5.11 where we show the mean aggregate flow on the phases of both feeders for increasing static phase transfers. This negative effect of static phase transfers may be due to the high variability of flows during the day, maintaining the network in an unbalanced state most of the time, despite of load on each feeder being better-balanced in average.

For the dynamic approach, we have better performance with the deployment of additional switches, except for day 1 on scenario A, in which adding the second and forth switches deteriorates the maximum VUF performance (see Figure 5.9a). The reason for this is that after adding the first switch on feeder 1 the maximum VUF is experienced on feeder 2 for all days except for Day 1 (Sunday). Once we add the second phase switch, this time in feeder 2 (as it is the one with the highest VUF in average), the maximum VUF is improved in feeder 2 but gets slightly deteriorated in feeder 1. Transferring phase connections on one feeder may negatively impact the others, as phases of different feeders are connected to a common busbar and the highest loaded phase may be different among feeders. This behavior is illustrated in Figure 5.12 by showing the maximum VUF of both feeders for the four dynamic switching cases. Feeder 1 values are in strong colors and Feeder 2 in light colors, with purple representing the scenario without phase switching, blue the data of day 1 and green the data of the rest of days, for 1 to 4 phase transfers. It can be clearly seen that for Day 1 the highest VUF is always experienced on feeder 1, while the rest of days the maximum value alternates according to the deployment of new phase switches. We see than in most cases adapting phases in one feeder slightly increases the maximum VUF on the other.

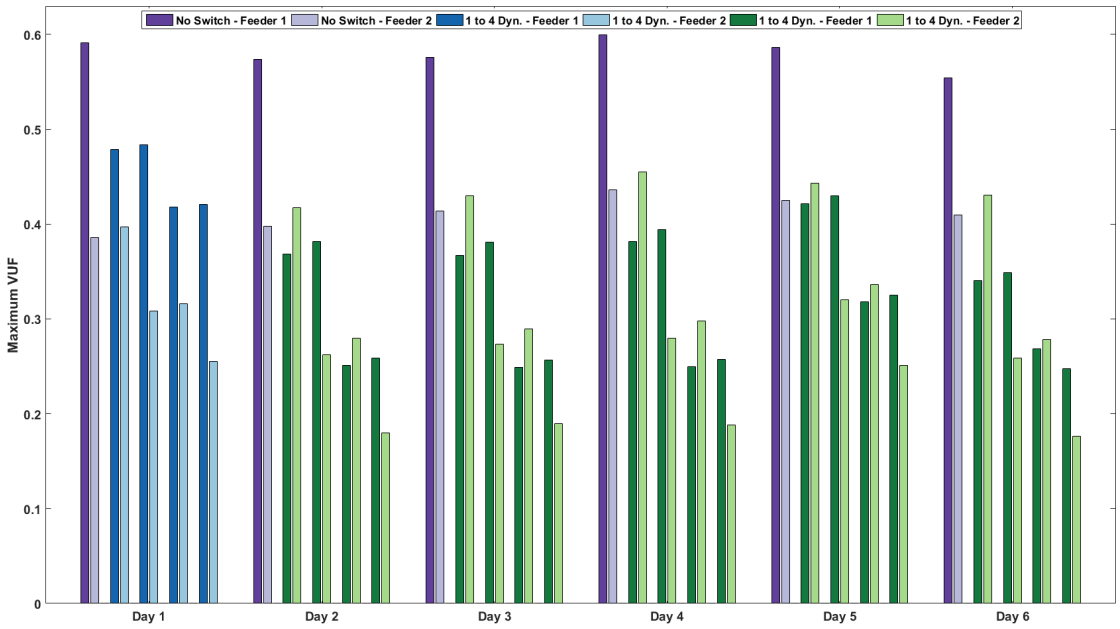


Figure 5.12 – Maximum VUF values per feeder for scenario A.

Next, we analyze the complete evolution from scenario A to D. First, we want to know which is the minimum number of phase switches to counteract the negative effect of the scheduling mechanisms for all days along all scenarios. For the static approach, 12 phase transfers are needed (2 in scenario A, 6 in B, 1 in C and 3 in D), while for the dynamic approach only 3 are enough (1 in A, B and C), which represents 24% of households against only 6% for the dynamic case.

In Figure 5.13 we can observe the reduction of peak VUF achieved with the minimum amount of phase switches. The scenarios are represented as areas ordered from A to D, yellow to red colors represent the static approach, while green to blue represent dynamic results. Note that for Scenario D, the static approach barely achieves the goal, which would require an extra phase transfer for different load conditions, while the margin for the dynamic approach is close to 20%.

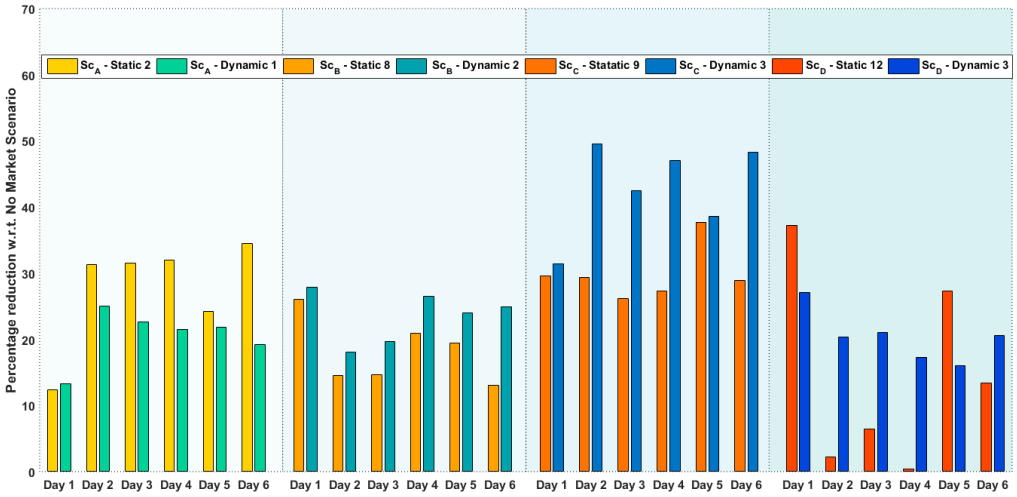


Figure 5.13 – VUF reductions achieved with minimal static switches vs. minimal STS.

Another interesting question is how many STS are needed to outperform in all cases the static approach in terms of VUF and Voltage rise/drop. The result obtained in this case is that 6 dynamic phase switches (2 in A, 2 in C, and 2 in D), representing 12% of total households, are enough to consistently achieve a better performance. Figure 5.14 shows the peak VUF reductions obtained with 6 STS compared with 12 static phase transfers. Notably, the results are the same for the initial scenario with the same amount of phase switches, but as more DER are deployed, the comparative performance gets considerably improved.

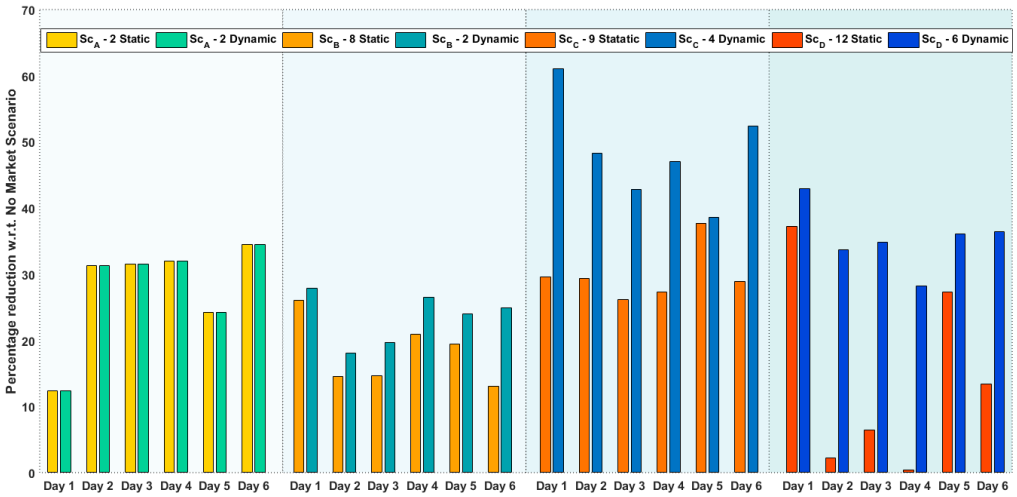


Figure 5.14 – VUF reductions achieved with minimal static switches vs. superior performance dynamic switches.

With respect to Voltage rise/drop, in Figure 5.15 we can observe the maximum voltage rise/drop experienced without scheduling, with static phase transfers, and with DPS. The results obtained show that, in general terms, better-balancing the network can significantly reduce peak voltage rise/drop, even if neither the algorithm nor the selection mechanisms consider it explicitly. In particular, DPS outperforms static phase switching with half the switches. Note that in scenario B, from day 2 to 4, the static mechanisms actually increases voltage.

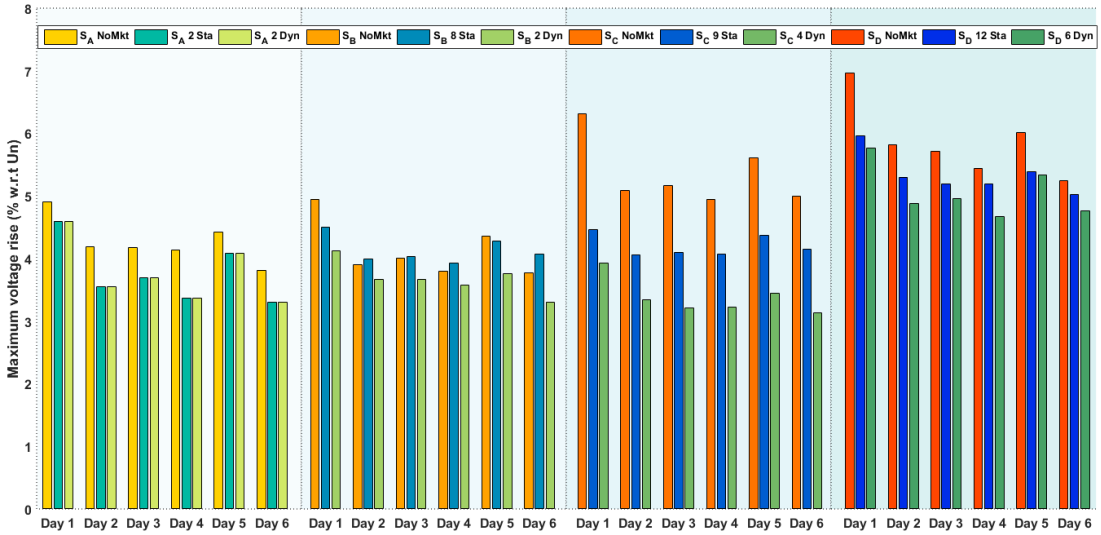


Figure 5.15 – Maximum Voltage rise with minimal static switches vs. superior performance dynamic switches.

Analyzing results and phase allocation decisions, we realized that adding extra phase switches, or simply considering voltage issues in the selection of households to switch or in the allocation itself, could enable further reductions of peak voltage rise/drop. Nevertheless, there may be a trade-off between VUF and Voltage reduction, as in some cases the phase allocation that would reduce the voltage level would also increase the VUF. Such an allocation should not be discarded, as long as the VUF is at acceptable levels. In future work, we will explore such modifications to the algorithm that may provide an even better performance without adding complexity.

With respect to losses, DPS outperforms static phase switching, with half the deployments of technicians. An interesting aspect of loss reduction is that the economic benefits obtained therein could be enough to finance the deployment of STS. The average total line losses reduction obtained across scenarios is of around $2.5MWh$ per year, which would represent a reduction of $100€/year$ for each 50 household neighborhood[14], considering an average electricity price of $40€/MWh$. If we consider that each scenario will last 5 years, during the first scenario the DSO will have to install 2 phase switches, but will recover $500€$ in loss reduction, then during the scenario B no additional phase switch would be needed, but around $500€$ would be saved on the neighborhood during the period. At the end of the 20 year period, for each 50 household neighborhood, the operator would have installed 6 STS and saved $2000€$, which would mean more than $300€$ for the deployment of each device. This is without taking into account the economic benefits of reducing VUF and Voltage rise/drop under massive deployment of DER. Such a discussion is only for illustrative purposes of the possible economic feasibility of DPS[15].

[14]Note that this is not negligible as in France there are more than 30 million residential clients.
[15]Note that OPEX costs are not considered in this analysis

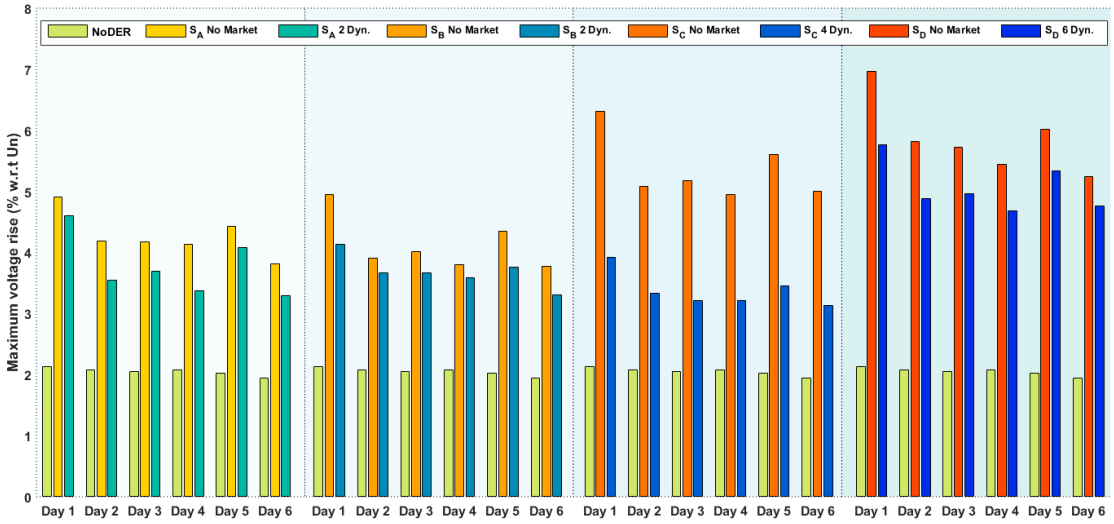


Figure 5.16 – Voltage drop/rise compared to NoMarket and NoDER scenarios.

Finally, in Figure 5.16 we show the voltage deviations (with respect to the nominal value) obtained by DPS in comparison with a scenario without market and a scenario without DER. We can see the voltage levels obtained at scenario D (80% of renewable energies) with our system are lower than those obtained in scenario C (50% of renewable energies) for a scenario without market. The same is valid for scenario C with respect to scenarios A and B. This represents an increase in hosting capacity with respect to voltage rise/drop. With respect to VUF, we obtain for scenarios B, C and D, a similar performance to the scenario without DER, and that only requires to add two phase switches for each scenario transition, up to a total of 6 (12% of households).

6 Conclusions and perspectives

A massive deployment of distributed renewable energies is one of the main vehicles towards the energy transition, but it can only be realized by extending the hosting capacity of distribution networks. The recent developments on local energy markets, exploiting residential storage and flexible loads to balance renewable energy flows at the neighborhood scale, have the potential to increase such capacity. Nevertheless, as most scheduling mechanisms, they create further imbalances in flows across phases, which favor higher voltage rises/drops and network losses. In this chapter, we address the impact of scheduling mechanisms on network unbalance. We propose Dynamic Phase Switching as a mechanism to cope with these issues by coordinating phase switching decisions with market decisions. The mechanisms are simple, they rely only on the information obtained from market decisions about the flows exchanged among households.

We provide a thorough assessment of the performance of the system, showing that only a small set of households (6%) need to be equipped with Solid State Switches to counteract the negative effects of scheduling mechanisms while maintaining all their benefits. Moreover, by deploying switches in 12% of total houses, voltage deviation levels can be maintained despite almost doubling the amount of renewables (e.g. from 25 to 40 houses equipped with Ptovoltaic panels) and the Voltage Unbalance Factor performance is similar to the one observed on a setting without Distributed Energy Services. Combining the benefits of local energy markets with cost effective Dynamic Phase Switching mechanisms we can effectively increase the capacity of distribution grid for hosting renewable energy. Furthermore, as mentioned along the paper, based on the proposed architecture the quality of supply

can be further improved, by introducing more advanced phase switching decisions, based for example on machine learning, in order to better exploit the data available to the Distribution System Operator.

Chapter 6

Real-time adjustment of market decisions

1 Introduction

We consider future distribution grids in a context of massive deployment of Renewable Energy Sources (RES) and storage technologies, in which a considerable percentage of households is equipped with PhotoVoltaic (PV) panels on their roofs and/or storage facilities. Maintaining quality of supply in such a context will require infrastructure reinforcements as usual, but also an active participation of Distribution System Operator (DSO) into the energy management of flexible Distributed Energy Resources (DER). This can be achieved through Demand Side Management (DSM), in particular, by gaining access to flexibility from residential prosumers, as they will own a considerable share of flexible DER.

A myriad of DSM mechanisms have been proposed and applied for the scheduling of such flexible resources [26, 80–82], from which the most relevant ones are those that provide incentives to prosumers for their active participation in distribution grid balancing as selfish agents [31,33,83,84] i.e.: Enable prosumers to reduce their electricity bill, while respecting distribution grid operation constraints. In particular, we will consider a local renewable energy market that enables households to agree with each other one hour-ahead of time on the exchange of renewable energy (This mechanism was presented on Chapter 4). Such markets, as well as all energy management mechanisms that rely on ex-ante agreements (day-ahead, hour-ahead, etc.), imply agents subscribing commitments on future energy flows. Nevertheless, such flows cannot be forecasted with high precision due to their dependency on human behavior and on exogenous variables controlled by nature (temperature, sunshine and wind). Thus, in order to cope with the uncertainty of demand and local renewable production, a real-time control of energy resources must provide the means to drive households towards a final exchange with the grid that benefits both prosumers and DSO.

In this chapter we address the control of electricity flows on a residential low voltage distribution grid in real-time. We propose a game theory model that enables households to decide which electricity flows to exchange with the distribution grid in order to minimize their costs. Such costs depend on their individual strategy and also on a penalty signal associated to a coupling constraint on the average strategy of all households. This establishes a game that enables households to optimize their own costs while reducing voltage rises/drops and current flows on the lines.

The main contributions of this work are the following:

- We rely on game theory results to model the interactions between a distribution system operator and prosumers for the control of their electricity flows in real-time, with the aim of reducing voltage rises/drops and current flows on the lines.
- The proposed game has a competitive aggregative equilibrium that can be attained through dynamics that only require one-to-all broadcast of price signals that do not depend on the amount of players.
- To the bests of our knowledge our work is the first to propose a real-time semi distributed mechanism for the control of residential electricity flows in a context of massive deployment of renewable energy sources and storage, that requires minimum communication, reduces both voltage deviations and thermal constraints.

2 Related Work

In a context of massive deployment of renewable energy sources and storage resources, DSO face the challenge of ensuring reliability and quality of electricity supply of distribution grids. For this they must deploy control mechanisms in order to maintain voltage inside the range imposed by regulation[1] and to avoid power flows reaching distribution lines' thermal limits. As the time of response needs to be in the order of 10 minutes, we focus on the literature related to real-time control on distribution grids.

Several approaches consider individual households optimization strategies as a response to real-time pricing [85–87]. In spite of being referred as real-time approaches, [85, 86] propose an hour-ahead scheduling that responds to real-time prices rather than focusing on a finer-grained control like in [87]. They do not consider RES nor the local distribution grid needs neither the coupling constraints among households. In [88], they consider the online control of an individual household with RES and storage under unknown arbitrary dynamics, nevertheless the model does not take into account the possibility to inject the excess of production on the grid and its corresponding negative effects on distribution grid operation.

Several centralized approaches have been proposed for real-time energy management in distribution grid systems [26–28]. The difficulty in such approaches is that flexible DER are owned and controlled by households, which hold the local information needed for a centralized control and will release part of this information only if adequate incentives are provided. In [29] and [30] authors propose decentralized mechanisms with the objective to flatten the aggregated demand of a large population of agents representing households. They do not consider distributed RES and, as the scale is larger than local distribution network, they do not take into account DSO constraints. They empirically demonstrate the mechanism is capable to achieve a desired emergent behavior (only a price must be sent to Smart Meters) if the probability of a household to adapt to price changes and the learning rate are low enough. In [31] they consider the goal of the Utility is to maximize social welfare, which is achieved in a distributed fashion by households optimizing their own benefits.

Game theory has been applied mainly to day-ahead energy scheduling, and particularly to modeling the game between the Utility and the consumers with the goal of minimizing energy costs [31–35]. In [33] they propose a Stackelberg game model that would allow Utilities to define prices that lead to an equilibrium that minimizes Peak to Average Ratio (PAR). In [34] they follow the same approach from [33], but with a strictly convex cost function that could take into account the injection of energy by households, but they do not consider distributed generation on their model. In [35], an online ver-

[1] Usually it cannot go over or under 10% of the nominal value ($400/\sqrt{3}$) for more than 10 minutes. In the case of overvoltage, the PV inverter must get disconnected from the grid

sion of a scheduling mechanism for flexible appliances is proposed, which copes with price prediction errors by updating the scheduled energy consumption each time the utility proposes a new price.

The works discussed before, in most cases, do not take particular care of the local voltage or thermal constraints. In the following we will address the existing literature on mechanisms for voltage control and thermal constraints, with a particular focus on voltage control only because it has been more studied than thermal constraints.

On-Load Tap Changer (OLTC) at the transformer or Step Voltage Regulators approaches for the online control of voltage have been proposed [89, 90], nevertheless these mechanisms are not well suited for real-time reaction due to increased work stress resulting in reduced system lifetime under high PV penetration [91]. Moreover their action is only global. As such it won't be able to solve over-voltage and voltage drop situations occurring at the same time on the same LV distribution network.

In [92] a centralized and a distributed active/reactive power control mechanism are compared using power flow analysis with respect to their impact on voltage violations and on thermal losses; results show that both offer significant gains in voltage reductions, but provoke a substantial increase on losses. In [93], authors propose a decentralized control of distributed generators active and reactive power in order to respect both voltage and thermal constraints. The mechanism proposed is based on persistence forecasting and local sensibility measurements, based on which distributed generators automatically update their output, without any coordination or communication. The demand of households as well as the incentives for households to comply with the required control are not considered. In [94] the authors propose a game-based local Volt/Var control mechanism where the strategic iteration among players is through the voltage on their Point of Common Coupling (PCC). In [95], a voltage control game is proposed where buses decide on their reactive power exchange with the grid with the aim of minimizing the local voltage deviation from its nominal value and taking into account the cost of providing reactive power control.

With respect to reactive power control on PV inverters, in most cases regulations require inverters to operate in power factor control mode, maintaining a fixed power factor, which leads to an injection on the grid mainly determined by the MPPT (Maximum Power Point Tracking) mechanism. This operation mode is less disruptive for network voltage control devices such as OLTCs in comparison with automatic voltage regulation [92]. Furthermore, reactive power control may result in higher currents and losses in the feeder [96] and may require to increase the power rating of inverters.

Active power curtailment is thus considered more effective than reactive power control for voltage regulation due to high R/X ratio on distribution networks [96], but requires costly compensations for the power that prosumers are not able to harvest or sell. Nevertheless, batteries or flexible load can be considered as an alternative to active power curtailment as the excess of energy can be stored on the battery for later use. Then the challenge becomes how to coordinate the active power flows exchanged with the grid from selfish agents representing households. With respect to approaches relying on active power control, in [97] they characterize the set of possible increments in power injection that respect voltage constraints and then define a game in which the sources of power coordinate a fair distribution of power injections. They do not consider storage in their model and the objective function of households does not reflect the necessary incentives for selfish agents.

In regards to the state of the art described above we will propose a competitive aggregative game model for the control of electricity flows exchanged with the grid by agents representing households equipped with renewable energy sources and flexible demand or storage. We exploit the energy market proposed in Chapter 4 as the hour-ahead scheduling mechanism, which provides incentives for households to reveal part of their private information through the exchange of energy with their neighbors. We rely on the results of Grammatico [43] to show that the game has an aggregative equilibrium, which can be attained using a semi-distributed mechanism that requires minimum communication and is scalable. One of the main hypothesis of the work by Grammatico relies on the operator/controller having access to the average response from agents to the control signals, which

is hard to achieve in practice for ex-ante models, as the operator would have to receive from households the entire set of optimal responses to the broadcasted control signals in order to compute the average population state. Such interactions would hinder one of the main advantages of this model which is one-to all coordination, and information exchanged would become dependent on the amount of agents. The controller can still decide on the step sizes of the iteration towards the equilibrium and on the stopping criterion, but as there is no commitment on every iteration, the game may be exposed to malicious agent behavior. Furthermore, the physical aspect of the network is not taken into account. In our case, as we consider an application of the results obtained by Grammatico to a real-time model, we can fully exploit its advantages, by relying on real exchanges of energy as a measure of the response of the agents to the control signal. This maintains one-to-all coordination and favors truthful responses from agents.

3 System Description

The low voltage distribution grid under study is the same that was considered in Chapter 5, with one or more three-phase four-conductors feeders to which four types of households (with different distributions of resources: PV, batteries and flexible loads) are connected, all equipped with smart meters and with the possibility of controlling the flows they exchange with the electricity grid. Households count on an energy management function (Home Energy Management System (EMS) (HEMS)) to optimize the allocation of electricity flows to DER depending on prosumer policies and economic incentives. The HEMS has access to real-time energy consumption data from the smart meter through the TIC interface [21], which can be made available wirelessly thanks to devices such as the ERL [98] or the BlueTIC [22].

The interactions between the operator and the prosumers will be carried out through the architecture introduced in the first part of the manuscript, and particularly relying on the distributed transactive platform. Households will agree on the exchange of energy with each other through a local energy market as described in Section 3.1. Then, a Real-Time Control (RTC) mechanism described in Section 3.2 will provide the means to drive households towards a final exchange with the grid that takes into account the contracted minimum value agreed on the hour-ahead market and the quality of supply requirements from the DSO. The RTC mechanism will be combined with Dynamic Phase Switching as described in Section 3.3 for balancing load across phases.

3.1 Local renewable energy market

In this chapter we will assume the existence of an ex-ante mechanism as proposed in Chapter 4, where houses agree one hour-ahead of time, through a distributed market, on the amount of energy they will exchange with each other (through the grid) on a 10 minutes basis. In addition to the exchange with neighbors, any remaining energy flow is contracted with the supplier through the transacting platform. Thus, an hour-ahead commitment has two components, one contracted with the neighbors and other with the supplier.

With respect to prices and auto-consumption, we consider the same conditions than in previous chapters. In particular, we assume that the market offers an incentive for locally balancing renewable energy, by providing a reward[2] for the energy that is certified to be balanced locally (through the market). In addition, suppliers may offer a smaller reward to enforce their part of the commitment, as they must provide the power for any extra (above local market quantities) electricity demand and would have to buy any excess of production. Such rewards motivate agents to enforce their contracted

[2]The reward is obtained by reforming the current Feed In Tariff mechanisms with the aim to correlate the incentive for producers to inject renewable energy with the availability of demand to absorb the energy locally.

quantities in real-time, by absorbing all or part of their forecast errors with their batteries or flexible loads.

3.2 Real-time control mechanism

Just before each time slot begins, prosumers will update their forecast for the next 10 minutes and will decide up to which point the error will be absorbed by their flexibility budget[3] or by the electricity supplier, through the distribution grid. Relying on flexibility has a cost related to the degradation of the battery or to the degradation of comfort, while deviating from the hour-ahead committed quantities implies loosing part of the reward as well as the beneficial price. The costs of relying on extra flexibility, the final electricity price and the allocation of rewards as prosumers deviate from the quantities planned hour-ahead are described in Sections 4.3, 4.4 and 4.5 respectively.

From the DSO perspective, the quality of electricity supply may be seriously affected by household decisions. For this reason, in addition to the individual cost mentioned above, during the time slots of high excess of production or demand, households will be charged a penalty fixed by the DSO, associated to a constraint on the average flow that neighbors exchange with the grid. Such a price signal would allow the DSO to influence the decision of household towards a final exchange with the grid that reduces voltage rises/drops and current over the lines.

The DSO will monitor voltage and current levels at each PCC for each time slot to detect any potential impact of flows on grid reliability and quality of supply. If at any time slot the voltage deviations or the current flows over the lines are close to voltage drop/rise or thermal limits, the RTC mechanism is applied on the next time slot. Such a monitoring could be realized only during the time slots in which the excess of production is high or in which the electricity demand is high.

3.3 Dynamic phase allocation

Before applying the RTC mechanism it is important to ensure that the flows across phases are as evenly distributed as possible in order to improve its performance. We assume the operator is capable of deploying solid state switches in a subset of households and of controlling dynamically their allocation to phases as described in Chapter 5. This functionality is complementary to the mechanism proposed in this chapter which is not particularly aimed to balancing load across phases.

4 Model

We consider a set of competitive agents $\mathcal{H} = \{1, 2, \ldots, H\}$ representing prosumers and a set $\mathcal{N} = \{1, 2, \ldots, N\}$ of logical nodes on the feeder where the connections of several households are aggregated[4], refereed to as PCC. A household is connected to only one PCC. Households control the amount of energy exchanged with the grid by using demand flexibility from batteries or flexible loads[5]. The goal of the operator is to influence the decision of households in order to enforce voltage deviation and current flow constraints.

[3]The hour-ahead market optimization limits the battery usage to one daily cycle and to depth of discharge smaller than its total capacity in order to extend the battery lifespan. The flexibility budget is the extra energy capacity of the battery, or of flexible appliances, reserved to absorb forecast errors.

[4]e.g.: where points of measurement are deployed or where a branch that feeds several households starts.

[5]We model the flexibility of loads as a small battery. A comprehensive model of demand elasticity depends on the type of appliances and their usage patterns, which are out of the scope of this work.

4.1 State of agents

The state of agents is composed by demand and production forecasts, by the quantities transacted on the hour-ahead local market, and by the state of the battery at the beginning of the current time slot, determined by the State of Charge (SoC) and by the accumulated charge/discharge quantities. For each agent $i \in \mathcal{H}$, the ex-ante mechanism scheduled the usage of the battery for the current time slot to be $\hat{s}^i$, in order to exchange $\hat{x}^i = \hat{x}^i_m + \hat{x}^i_u$ with the grid, where $\hat{x}^i_m$ and $\hat{x}^i_u$ are the amounts traded with neighbors and with the supplier respectively, under a forecasted gap $\hat{r}^i$ between production $\hat{g}^i \in \mathbb{R}^N_{\geq 0}$ and consumption $\hat{l}^i \in \mathbb{R}^N_{\geq 0}$ according to the following balance equation

$$\hat{x}^i_m + \hat{x}^i_u + \hat{s}^i = \hat{l}^i - \hat{g}^i = \hat{r}^i \tag{6.1}$$

A closer to real-time forecast or a Very Short Term Load Forecast [36] enables each house to update its gap between consumption and production as $r^i = \hat{r}^i + \tilde{r}^i$, where $\tilde{r}^i = \tilde{l}^i - \tilde{g}^i$ is the error on hour-ahead production and load forecasts.

4.2 Agents' strategies

The real-time control of each household aims to decide at which extent the error $\tilde{r}^i$ will be absorbed by the grid or by demand flexibility. Thus, each agent i decides on a strategy (x^i, s^i), where $s^i \in \mathbb{R}^N$ represents the amount of energy charged (negative) or discharged (positive) to/from the batteries and $x^i \in \mathbb{R}^N$ is the total amount of energy to be exchanged with the grid on the current time slot (includes the energy exchanged with neighbors and with the electricity supplier). The relationship between the battery flow s^i and the grid flow x^i is $x^i + s^i = l^i - g^i = r^i$, the same as in (6.1).

4.3 Batteries

The amount of energy stored in the battery of household i at the end of current time slot is represented by $e^i \in \mathbb{R}^N$. Its evolution in time is given by $e^i = e^i_0 - s^i$, where e^i_0 represents the energy on the battery at the beginning of current time slot.

The operation of batteries or flexible loads must respect the following constraint:

$$\max[e^i_0 - \overline{E}^i, \underline{s}^i, \underline{e}^i] \leq s^i \leq \min[e^i_0 - \underline{E}^i, \overline{s}^i, \overline{e}^i] \tag{6.2}$$

which bounds the use of the battery to the intersection of three segments:

Energy capacity states that the battery cannot be discharged or charged beyond its minimum or maximum energy levels, $\underline{E}^i$ and $\overline{E}^i$ respectively. In order to preserve the battery lifetime, the values $\underline{E}^i$ and $\overline{E}^i$ usually correspond to a SoC around 10-20% and 80-90% of the battery capacity respectively. For instance, the hour-ahead scheduling mechanism limits the battery capacity available for finding the optimal market offers to a range of SoC between 25% and 75% of total battery capacity, reserving a share of the capacity for the RTC mechanism, which can use a depth of discharge between 10% and 90%. This capacity reserved for the RTC mechanism will be available at the expense of an additional cost, introduced in (6.3), representing battery degradation as we deviate from the hour-ahead planned use of the battery $\hat{s}^i$.

Power capacity represents the minimum and maximum energy that can be exchanged with the battery on a time slot, $\underline{s}^i$ and $\overline{s}^i$ respectively.

Cycling capacity $\underline{e}^i$ and $\overline{e}^i$ represent the charging and discharging cycling constraints. For instance, the hour-ahead scheduling mechanism limits the battery usage to one cycle per day, while up to an extra cycle per day can be exploited by the RTC mechanism to absorb forecast errors, at the expense of a degradation cost. The cycling capacity constraint is allocated to individual time slots in proportion to the corresponding day-ahead forecasted production. The reason for such an allocation is that during sun hours the variability of forecast errors is higher and thus both the prosumer and the operator need more flexibility.

We denote $\mathcal{S}^i \in \mathbb{R}^N$ the set of flows that satisfy the constraints described above. For batteries operating under such constraints, the degradation costs are expressed as

$$C_e^i(s^i) = a^i(s^i - \hat{s}^i)^T(s^i - \hat{s}^i) + {b^i}^T(s^i - \hat{s}^i) \tag{6.3}$$

where s^i and C_e^i represent the use of demand flexibility and its corresponding costs[6], regardless of the source of flexibility being the battery or the elasticity of demand. In the case of batteries, $a^i = a_s^i$ and $b^i = b_s^i$ are parameters that must be chosen adequately to ensure that the costs for an extra use of the battery are compensated by the economic incentives, depending on battery characteristics [99] and on the flexibility budget reserved for the RTC mechanism. For the case of flexible loads, $a^i = a_l^i$ and $b^i = 0$ represent a purely quadratic disutility function as was already proposed in [68, 100].

4.4 Final electricity prices

With respect to prices, we need to take into account the two components of the hour-ahead commitment of each agent $\hat{x}^i$, which are the quantity $\hat{x}_m^i$ traded with neighbors at price P_m^i and the quantity $\hat{x}_u^i$ contracted with the supplier at price P_u or at the Feed In Tariff (FIT) P_f depending if the prosumer is buying or selling. The price to pay for the effectively exchanged flow x^i will be the following:

$$C_p^i(x^i) = (x^i - \hat{x}_m^i)p + \hat{x}_m^i P_m^i \tag{6.4}$$

where

$$p = \begin{cases} P_u, & \text{if } x^i >= \hat{x}_m^i, \\ P_f, & \text{else,} \end{cases} \tag{6.5}$$

Such a price allocation models the fact that a household i that consumes or injects more than what was agreed on the market is considered to have enforced the market transaction and the extra energy flow measured by the DSO will be charged/payed at the corresponding price P_u or P_f. While, for instance, if the house consumes[7] less than agreed on the market, an excess of injection will be absorbed by the utility (assuming the corresponding producers injected the contracted quantity); the prosumer will then pay $x_m^i P_m^i$, but will receive $(x_m^i - x^i)P_f$, which corresponds to the payment owed by the utility for the energy absorbed. Note that the difference in prices ($P_f < P_U$) makes enforcing the transaction more profitable in terms of electricity payment.

[6] Note that no degradation cost are considered when the battery is operated exactly as planned one hour-ahead (daily optimal operation of the battery).

[7] The logic is similar if an agent agrees to inject energy for their neighbors.

4.5 Reward allocation

The reward attribution depends on the deviation from the hour-ahead committed quantities as follows:

$$C_r^i(x^i) = a_r^i(x^i - \hat{x}^i)^T(x^i - \hat{x}^i) - R \tag{6.6}$$

where the value R is defined one hour-ahead as a percentage of the transacted quantity. The reward gets reduced quadratically as the agent i deviates from the hour-ahead committed quantity $\hat{x}^i$. Note that if the deviation is too big the reward becomes a penalty.

4.6 Aggregative Constraint

The strategies of households are coupled by an aggregative constraint that enables DSO to favor a better quality of supply. The constraint over the average strategy is as follows:

$$\underline{c} \leq \frac{1}{H}\sum_{i=1}^{H} x^i \leq \overline{c} \tag{6.7}$$

where $\underline{c}$ and $\overline{c} \in \mathbb{R}^N$ are the aggregated load constraints at the set of PCC, which are defined by the operator according to the expected flows for the current time period. We denote as $\mathcal{C} \subset \mathbb{R}^N$, the set of $\frac{1}{H}\sum_{i=1}^{H} x^i$ such that (6.7) is satisfied.

We rely on load flow sensibility analysis to determine which are the maximum permitted power variations on each PCC. Sensibility analysis enables in particular to determine which would be the impact of a variation in power on voltage values at each PCC and on currents over line segments.

This is achieved by running several power flow calculations, each adding perturbations on each of the flows until a constraint violation is detected [28]. In particular, for a period of high injection we progressively increase the aggregate injection and we allocate the increase to individual household in proportion to their injection on the previous time slot. When a constraint is detected, the injections on the previous iteration are considered as the maximum power transit supported by the grid for the time slot.

This procedure requires specific knowledge about the grid infrastructure (nodes, lines, impedances, etc.), which is not necessarily available for distribution grids. Such information can be estimated by using measurements of power injection and voltage and current variations [37,38]. Furthermore, it is possible to estimate the structure of the power grid exclusively from PCC nodes measurements [39,40] or from smart meter's measurements [41], even with missing data from certain of nodes [42]. This would enable to establish short measurement campaigns after which a model of the grid and its sensibility coefficients can be obtained. Machine learning techniques can be applied to detect when the model performance degrades, and when to launch a new measurement campaign for a model update.

4.7 Problem definition

The goal of each agent $i \in \mathcal{H}$ is to find a strategy x^i such that

$$x^i \in \arg\min_{y} J^i\left(y, \frac{1}{H}\left(\sum_{j=1}^{H} x^j\right), \lambda\right) \tag{6.8}$$

s.t.

(6.1)

(6.2)

$$y \in [-\overline{x}^i, \overline{x}^i] \tag{6.9}$$

where, J^i is the local cost function which depends on the average among the strategies of all the agents and on λ which represents a penalty associated to the coupling constraint in (6.7). The parameter $\overline{x}^i$ in constraint (6.9) represents the energy corresponding to the maximum power capacity contracted with the supplier by household i. We denote with $\mathcal{X}^i$ the set of feasible values of x^i.

The cost function $J^i : \mathbb{R}^N \times \mathbb{R}^N \to \overline{\mathbb{R}}$, with $\overline{\mathbb{R}} := \mathbb{R} \cup \infty$ is defined as follows:

$$J^i(x^i, u) = f^i(x^i) + u^T x^i \tag{6.10}$$

where the function $f^i(x^i)$ reflects the costs that depend only on the individual strategy, which are the sum of battery/comfort degradation costs, reward allocation and final electricity pricing[8]

$$f^i(x^i) = C_e^i(x^i) + C_r^i(x^i) + C_p^i(x^i) \tag{6.11}$$

and u is a signal broadcasted (through the transactive platform) by the DSO, which is defined as

$$u(\sigma, \lambda) = D\sigma + K\lambda \tag{6.12}$$

Where $D = diag(d_1, \cdots, d_N)$ represents an electricity distribution fee on the average strategy of houses and the invertible $K \in \mathbb{S}^N$ (symmetric $N \times N$ matrix) is used to tune the weight of the penalty on each PCC.

5 Competitive aggregative game

The problem described above forms a competitive aggregative game, as the optimal response of an agent depends on the aggregate response of the rest of players and they all share a common penalty associated to coupling constraint. Grammatico proved in [43] that such a game has an aggregative equilibrium under assumptions on functions $\{f^i\}_{i=1}^H$ being l-strongly convex and on compactness, convexity and Slater's qualification [44] of the sets $\{\mathcal{X}^i\}_{i=1}^H$ and $\mathcal{C}$. Note that we need $\mathcal{C} \subseteq \frac{1}{H}\sum_{i=1}^H \mathcal{X}^i$ to avoid the operator fixing constraints that are not attainable with the feasible responses of households. For this we assume that the DSO can estimate the set $\frac{1}{H}\sum_{i=1}^H \mathcal{X}^i$. For instance, households could be asked to communicate their flexibility budget for every time slot in which the real-time control mechanism is activated. Aggregative equilibrium is defined as follows.

Definition 1: *Aggregative equilibrium*. A tuple $((x^{i*})_{i=1}^H, \lambda^*)$ is an Aggregative equilibrium, for the game described in (6.8) with the coupling constraint in (6.7) if $\frac{1}{H}\sum_{i=1}^H x^{i*} \in \mathcal{C}$, and for all $i \in \mathcal{H}$,

$$x^{i*} \in \arg\min_{y \in \mathcal{X}^i} f^i(y) + \left(D\frac{1}{H}\left(y + \sum_{j \neq i}^H x^{j*}\right) + \lambda^*\right)^T y \tag{6.13}$$

[8] Note that $C_p^i(x^i)$ are convex piecewise linear functions, while functions f^i are strictly convex and l-strongly convex for any $l \in \left[0, 2(a^i + a_r^i)\right)$.

5.1 Dynamic control algorithm of decentralized optimal responses

Such an equilibrium can be attained by following the semi-distributed approach proposed by Grammatico [43, Section III]. The mechanism relies on households responding optimally to the incentive signal u introduced in (6.12), as specified by the agent's optimal response mapping $x^{i*} : \mathbb{R}^N \to \mathcal{X}^i$, defined as

$$x^{i*}(u) := \underset{y \in \mathcal{X}^i}{\arg\min}\ f^i(y) + u^T y, \tag{6.14}$$

and on finding a fixed point σ^* of the optimal strategy aggregation mapping $\mathcal{A} : \mathbb{R}^N \times \mathbb{R}^n \to \frac{1}{H}\sum_{i=1}^H \mathcal{X}^i$, defined as

$$\mathcal{A}(\sigma, \lambda) := \tfrac{1}{H}\textstyle\sum_{i=1}^H x^{i*}(D\sigma + K\lambda), \tag{6.15}$$

such that $\sigma^* = \mathcal{A}(\sigma^*, \lambda^*)$ for some $\lambda^* \in \mathbb{R}^N$. Then, $\sigma^* = \frac{1}{H}\sum_{i=1}^H x^{i*}(D\sigma^* + K\lambda^*)$ and a pair $\left(\left(x^{i*}\right)_{i=1}^H, \lambda^*\right)$ is a competitive aggregative equilibrium as defined in (6.13), the existence of which is demonstrated in [43, Appendix A].

Then the goal is to find a pair of arguments (σ^*, λ^*) such that $\sigma^* = \mathcal{A}(\sigma^*, \lambda^*) = x^0$, for some $x^0 \in \mathcal{C}$. As a design choice let us define the mapping $x^{0*} : \mathbb{R}^N \times \mathbb{R}^N \to \mathcal{C}$ as

$$x^{0*}(\sigma, \lambda) := \underset{y \in \mathcal{C}}{\arg\min}\ \tfrac{1}{2} y^T y + (K(\lambda - \sigma))^T y, \tag{6.16}$$

Such a pair of arguments can be obtained by finding a zero of the mapping $\Theta : \mathbb{R}^{2N} \to \mathbb{R}^{2N}$ defined as

$$\Theta\left(\begin{bmatrix}\sigma\\ \lambda\end{bmatrix}\right) := \begin{bmatrix}\sigma - \mathcal{A}(\sigma, K\lambda)\\ \sigma - 2\mathcal{A}(\sigma, K\lambda) + x^{0*}(\sigma, \lambda)\end{bmatrix} \tag{6.17}$$

$$=: (M + \Gamma)\left(\begin{bmatrix}\sigma\\ \lambda\end{bmatrix}\right), \tag{6.18}$$

where the matrix $M \in \mathbb{R}^{2N \times 2N}$ and the mapping $\Gamma : \mathbb{R}^{2N} \to \mathbb{R}^{2N}$ are defined as follows

$$M := \begin{bmatrix} I_N & 0\\ I_N & 0\end{bmatrix} \tag{6.19}$$

$$\Gamma\left(\begin{bmatrix}\sigma\\ \lambda\end{bmatrix}\right) := -\begin{bmatrix}\mathcal{A}(\sigma, K\lambda)\\ 2\mathcal{A}(\sigma, K\lambda) - x^{0*}(\sigma, \lambda)\end{bmatrix} \tag{6.20}$$

where I_N denotes the Identity matrix of dimension N.

In order to find a zero of the mapping Θ, a dynamic control law κ is proposed in [43, Section III.C] such that $[\sigma_{(t+1)}, \lambda_{(t+1)}] = \kappa\left(t, [\sigma_{(t)}, \lambda_{(t)}]\right)$, defined as

$$\begin{bmatrix}\sigma_{(t+1)}\\ \lambda_{(t+1)}\end{bmatrix} := (1 - \alpha_t)\begin{bmatrix}\sigma_{(t)}\\ \lambda_{(t)}\end{bmatrix} + \alpha_t (I + \epsilon M)^{-1}\left(\begin{bmatrix}\sigma_{(t)}\\ \lambda_{(t)}\end{bmatrix} - \epsilon\Gamma\left(\begin{bmatrix}\sigma_t\\ \lambda_t\end{bmatrix}\right)\right), \tag{6.21}$$

where $\epsilon > 0$, the matrix K and the averaging steps sizes $(\alpha_t)_{t=0}^{\infty}$ are chosen following the design choices 1-4 in [43, Section III and IV], in order to ensure the existence and uniqueness of a zero of the mapping Θ and the convergence at a logarithmic rate of the dynamic control law in (6.21).

5.2 Iterative Process

An iterative process to attain an aggregative equilibrium starts at the beginning of the 10 minutes time slot with a period of around 10 seconds[9], which should enable households to adapt to penalty changes, while providing enough iterations for the semi-distributed algorithm to converge to the equilibrium. At the beginning of k-th iteration, the operator will estimate the aggregated optimal response $\mathcal{A}(\sigma_{(k-1)}, K\lambda_{(k-1)})$ on the previous iteration by measuring the flows on each PCC of the corresponding feeder. Then it will update the signal u, which will reach the prosumers through the next published block on the transactive platform. At the detection of a change in signal u, each agent will proceed to update its optimal response $x^{i*}_{(k)}$ from (6.14), by updating its battery optimal flow $s^{i*}_{(k)}$ from (6.1).

In each iteration, prosumers decide on the energy flow to exchange with the grid on the whole 10 minutes, while relying on forecast done at the beginning of the time slot and on measurements of energy flows and battery usage up to the current iteration. The relationships on the optimal flows for the entire time slot and the flows up to iteration k are as follows

$$x^{i*}_{(k)} = x^{i}_{0k} + x^{i}_{kT} \tag{6.22a}$$

$$s^{i*}_{(k)} = s^{i}_{0k} + s^{i}_{kT} \tag{6.22b}$$

where x^{i}_{0k} corresponds to the flow exchanged with the grid up to the k-th iteration and x^{i}_{kT} to the future energy flow up to the end of the time slot. The notation is the same for battery flows. Note that we assume households have access to the cumulated energy exchanged with the grid x^{i}_{0k}, through the smart meter, and to the corresponding battery usage s^{i}_{0k}, through the smart inverter/battery controller.

The model we apply is deterministic, as it does not consider that the state of agents can change during the negotiation process towards the equilibrium. It relies then on the forecast done by households at the beginning of each time slot to be perfect. An analysis of the sensibility to very short term forecast errors and the possibility of applying stochastic game theory are subjects of future research.

Under such a deterministic scenario, each household will define the battery setting for the rest of the time slot as follows

$$s^{i}_{kT} = r^{i} - x^{i*}_{(k)} - s^{i}_{0k} \tag{6.23}$$

where (6.1) and (6.22b) were used. Here we assume that households set their batteries to the value s^{i}_{kT} so that if the flows are maintained up to the end of the time slot the total flow exchanged with the grid during the time slot would be $x^{i*}_{(k)}$.

The iteration procedure towards an aggregative equilibrium is summarized as follows

[9] While the time between blocks on the blockchain-based transactive platform described in Chapter 3 is around 5 seconds.

Algorithm 2 Dynamic control of competitive optimal responses [43]

Initialization: $t \leftarrow 0$;
- The DSO chooses $(\sigma_{(0)}, \lambda_{(0)})$;

Iterate until convergence:
- DSO broadcasts $[\sigma_{(t)}; K\lambda_{(t)}]$ to all agents
- and computes $x^{0*}(\sigma_{(t)}, \lambda_{(t)})$ from (6.16)

  ∘ Each agent $i \in \mathcal{N}$ computes $x^{i*}(\sigma_{(t)}, \lambda_{(t)})$ from (6.14),
  ∘ then estimates battery setting s^i_{tT} from (6.23).

- DSO measures average best response $\mathcal{A}(\sigma_{(t)}, K\lambda_{(t)})$,
- computes $\Gamma([\sigma_{(t)}; K\lambda_{(t)}])$ from (6.20) and
obtains $[\sigma_{(t+1)}; \lambda_{(t+1)}] = \kappa(t, [\sigma_{(t)}; \lambda_{(t)}])$ from (6.21)

$t \leftarrow t + 1$

6 Simulations and Results

6.1 Procedure and system scenario

The simulation of the real-time control mechanism relies on local energy market results and on an allocation of households to phases that may be updated by a Dynamic Phase Switching (DPS) mechanism. Those two additional mechanisms are simulated following the procedures described in Chapter 4 and 5 respectively.

We consider the forecast used by households for the hour-ahead market to be a day-ahead persistence forecast, and the updated forecast just before the time slot to be perfect, which allows us to apply a deterministic model.

With respect to the monitoring period, the real-time control mechanism is only launched if during the previous time slot we detected a voltage deviation of 9% or a current flow above 70% of the thermal limit. To simulate such monitoring we realize load flow studies for every time slot in high sun hours (from 10 am to 2 pm), and for the cases where a risk of constraint existed the real-time control mechanism was launched.

We consider a distribution grid composed of two feeders and 50 households, 60% of which are equipped with a battery and 80% with a PV panel. All households participate on the market and are eligible for dynamic phase switching. With respect to the level of aggregation of households on each logical PCC, we consider one PCC per phase of the feeder. This means that the amount of PCC becomes $N = 3$ and all the houses on the same phase are considered to share the same logical PCC. This keeps the model simple and independent of the physical structure of the feeder and the distribution of households. Furthermore, the measurements needed by the DSO to implement the real-time control mechanism are currently available at this level of aggregation without the need of deploying further measurement devices.

6.2 Simulation tools and parameters

To implement the mechanism described in Algorithm 2, we use MATLAB [45] together with the Gurobi [46] optimization suite. For the power flow analysis, we rely on the Distribution Network Simulation Platform (DisNetSimPl) developed by EDF R&D. We use a slightly modified version of the electricity network model provided in Chapter 4, conformed by a 20 kV/410 V transformer of 160 kVA rated

power, two feeders with aluminum power lines of 150 mm^2 and a neutral conductor of 70 mm^2.

The parameters used for the simulations were the following:

Load profiles - We use realistic synthetic consumption data obtained from the Multi-agent Simulator of Human Behavior SMACH [25] as input for the household optimization problem. The load curves correspond to 7 winter days of consumption on a 1-minute basis from 50 households of mixed profiles.

Production profiles - We consider the same synthetic production curve for all the PV panels (all located on the same area), but the profile varies on a daily basis.

Batteries - We consider ideal batteries of 9kWh total capacity. Up to 6kWh (10% to 77%) are allowed to be used for local market exchanges in order to preserve the battery lifespan while reserving a share (1.2 kWh) of the capacity to the RTC mechanism, which can use up to 7.2kWh (10% to 90%) of the capacity for absorbing renewable energy. For the case of flexible appliances, whose elasticity is entirely reserved for the RTC mechanism, we consider up to 1 kWh of energy is available for coping with forecast errors[10].

Electricity prices - We consider a common supplier offering a Time Of Use pricing with two levels: 15 c€/kWh from 12 am to 4 pm and 20 c€/kWh from 5 pm to 11 pm. While the FIT is considered to be 10 c€/kWh.

Dynamic control algorithm - The iteration parameter $\alpha_k = 1$ for all k, the matrix $K = I_N$, and the convergence criteria $||\Theta([\sigma_{(t)}; \lambda_{(t)}])|| < 10^{-2}$.

6.3 Results and discussion

We analyze the performance of the RTC mechanism during the time slots with high renewable energy production (between 10 am and 2 pm). In particular, we are interested in cases where we observe that thermal or voltage limits are breached, or close to the limits, for the scenario without RTC. From the 7 days analyzed on the simulations we focus on the most critical day, both in terms of voltage deviations and current flows. First, we analyze voltage deviations with respect to the nominal value and then the reduction of current flows on lines. In both cases, we compare the RTC mechanism coupled with Dynamic Phase Switching (DPS) to a case without real-time incentives and without phase switching, in which the only difference for households optimization is that the signal u is 0 for all the time slots.

6.3.1 Reduction of Voltage deviations

We start by analyzing the impact of the RTC mechanism in voltage deviations with respect to the nominal value Un. In Figure 6.1, we see the voltage deviations along the feeder for the RTC mechanism coupled with DPS, compared to the case without RTC, which are represented by two surfaces, green and blue respectively. The red (planar) surface shows the voltage limit during the period in which RTC was active. During this period the RTC mechanism combined with DPS achieve consistent reductions of maximum voltage deviations, observed as the green surface (RTC + DPS) goes below the blue surface, while for the case without RTC the voltage limits are violated in two opportunities,

[10]This amount could be considered higher taking into account that only a water heater can consume more than 5kWh a day

when the blue surface goes above the red planar one. These results demonstrate the capacity of RTC combined with DPS for avoiding voltage limit breaches.

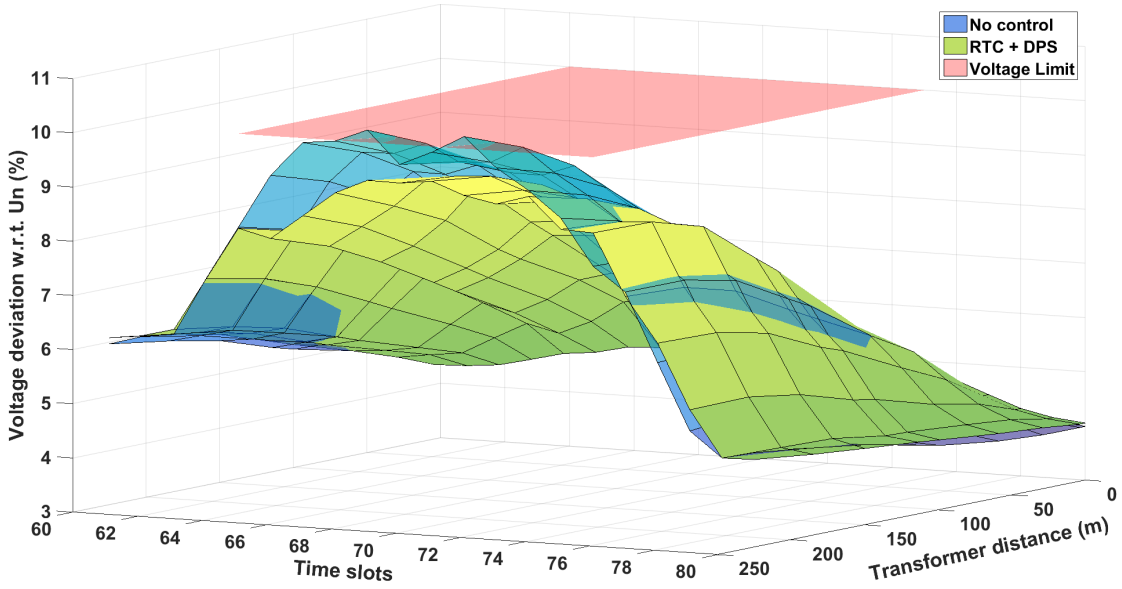


Figure 6.1 – Maximum voltage deviations along the feeder.

6.3.2 Reduction of current flows through the lines

With respect to the current flows through the lines, in Figure 6.2 we show the current intensity along the Feeder during the monitoring period. The red (planar) surface shows the thermal limit during the period in which RTC was active. During this period we can clearly appreciate considerable reductions of current intensity all along the feeder avoiding the violation of thermal constraints that are observed for the case without RTC. Such reductions are enough to avoid or postpone the replacement of entire line segments, which directly translates into a considerable reduction of infrastructure investment.

6.3.3 Dynamic control mechanism performance

With respect to the performance of the dynamic control mechanism to attain the aggregate equilibrium, we observed an improvement of the convergence speed first due to the combination with the DPS mechanism. Without the DPS mechanism the mean amount of iterations was over 60 (10 minutes), which would not be applicable to our setting without further tuning, but the DPS mechanism brought the mean convergence time to 5 minutes, with a maximum of 39 iterations, which is adequate for our setting. This is probably due to the fact that our level of logical PCC aggregation is the phase, and if the loads and their DER are better distributed among phases the mechanism converges faster. For instance, if one of the phases has little or no flexibility budget, then the convergence will be slower. Thus, the algorithm converges in around 5 minutes and then each household just needs to put the battery to track the optimal flow to exchange with the grid during the rest of the time slot.

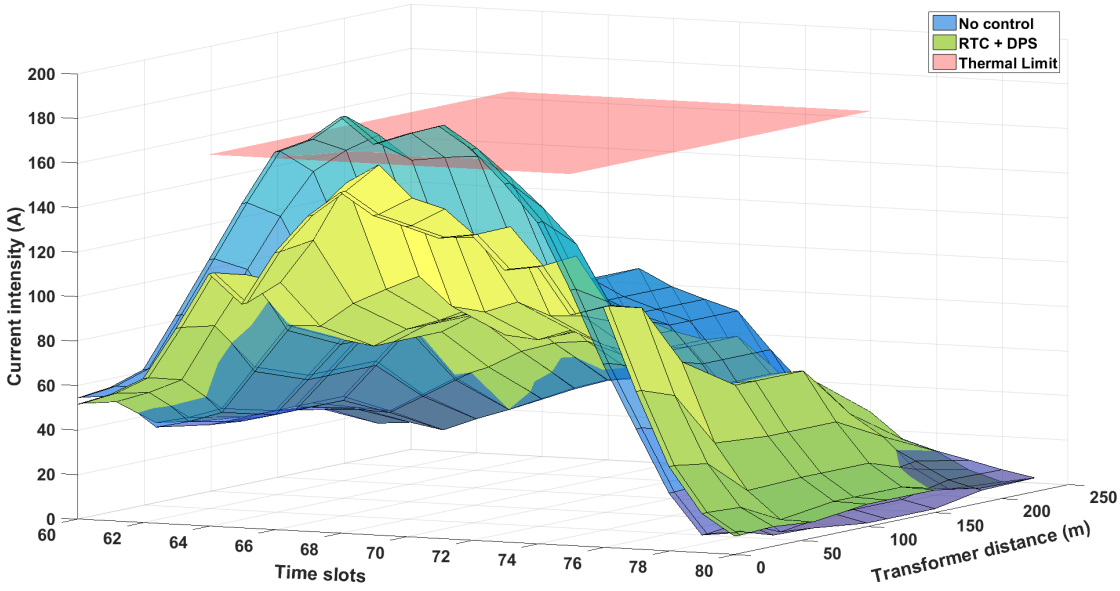


Figure 6.2 – Current intensity level along the feeder.

7 Conclusions and perspectives

Local energy markets enable households to exchange energy with each other while increasing the amount of renewable energy that is consumed locally. Such markets increase the capacity of distribution grids for hosting renewable energies, but, as all ex-ante mechanisms, local market schedules rely on hour-ahead forecasts whose accuracy may be low. We propose a game-based real-time control mechanism to cope with forecast errors by driving households to a final exchange with the grid that benefits both the prosumer and the DSO. The proposed game has an aggregative equilibrium which can be attained in a semi-distributed manner with a number of iterations independent of the amount of households.

The performance of the mechanism is evaluated through load flow analysis and realistic load curves for a scenario with 50 households, where 80% of them are equipped with PV panels and 60% with storage. The simulations show that without the control mechanism the grid would not be capable of hosting such level of penetration of renewable energies. However, when the real-time control mechanism is applied in combination with dynamic phase allocation, maximum voltage deviations and current intensities are considerably reduced, avoiding the violations of voltage deviation and thermal constraints. We show that the proposed real-time mechanism is capable of adjusting the flows issued from local market commitments towards an equilibrium that optimizes the prosumers' electricity bill while increasing the capability of the distribution grid to support the energy transition.

The performance of the proposed real-time market mechanism can be further improved by better selecting the parameters of the dynamic control scheme and of the local cost functions. With respect to the combination with the dynamic phase switching approach, the selection of households and the switching mechanism could be specifically adapted to further reduce voltage deviations. We are currently working on a sensibility analysis to very short term load/production forecast errors that could provide valuable insights for the development of stochastic game models.

Part IV

General conclusions and perspectives

Chapter 7

General conclusions and future work

1 General conclusions

The electricity industry is under major ongoing evolutions, in particular due to the local deployment of Renewable Energy Sources and storage capacity, which represent a key driver for the Energy Transition and related objectives. Nevertheless, present electricity distribution grids were not designed for facing massive deployment of renewable energy sources on residential premises, nor for the structural changes in load induced by the expected fast growth of the electric car market. The required transformations of the distribution grid are today delaying, and in some cases blocking, the possibility to leverage such opportunities. Demand side management mechanisms can play a key role in the integration of distributed energy resources, but with no architectural changes towards exploiting demand side flexibility, the required investments on infrastructure reinforcement may be extremely high.

In this thesis we propose a novel, cost-effective, architecture capable of fostering collaboration among wholesale market actors, Distribution System Operators and end customers (that become *prosumers*), to leverage flexible distributed energy resources while respecting distribution system constraints. The architecture is designed for providing innovative Residential Demand Side Management services, with a special focus on services enabled by self-consumption at the household and neighborhood level. We show that the architecture and related demand side management mechanisms we propose successfully alleviate congestion, reduce voltage deviations and losses, and consequently augment distribution grid capacity for hosting renewable energy sources. This was validated through comprehensive simulations using power flow analysis and realistic load profiles, providing valuable insight for the design of future distribution grid architectures and energy management systems.

In Part II of the thesis we propose the building blocks for future distribution grid energy management architectures, capable of providing residential Demand Side Management mechanisms and related energy services. In Chapter 2 we propose the functional and technological components for implementing a general IoT-based smart home architecture. We address some of the main challenges faced by IoT solutions, with a special emphasis on interoperability issues, by leveraging existing technologies and proposing a specific approach in terms of distribution of data and intelligence. In Chapter 3 we extend this architecture from home to the neighborhood level, which is the main focus of Part II. Given that the services we have defined (which we present in Part III) require transactions among the different actors, we also introduce in this chapter the components enabling to deploy a blockchain infrastructure. Moreover, to facilitate the management of the proposed smart distribution grid archi-

tecture, we propose a new paradigm, that we named Virtualized Distribution Grids. In this thesis we have not developed this concept further, which remains a relevant subject of future work. The rest of contributions of the thesis apply to both virtualized and non-virtualized distribution networks.

The general framework we propose in Part II facilitates the deployment of advanced technologies (local production, storage, building energy management systems, and other IoT-based on-premises technologies) and the coordination among any type of player (including Distribution System Operators, aggregators, and prosumers) to leverage those resources in a way that optimizes the overall value obtained while maintaining distribution grid reliability and quality of supply. The architecture, based on blockchain technology, satisfies the main architectural requirements for future distribution grid energy management systems, particularly in terms of infrastructure mutualization (cost-effectiveness), reliability, security, transparency and auditability.

In Part III, which holds the core contributions of the thesis, we propose novel services and mechanisms enabled by the architecture and we show their positive impact on the capacity of distribution grids for hosting renewable energies while maintaining the quality of electricity supply.

In Chapter 4 we propose a market approach that, on the one hand, enables households to autonomously exchange energy blocks with neighbors and with other market players, in order to optimize their electricity bill, and on the other hand, enables the Distribution System Operator to improve the reliability and quality of electricity supply. The proposed system is based on auction mechanisms and specific dynamic transport fee rebates that jointly designed provide incentives for households to locally manage energy resources in a way that favors the balance of renewable energy production with flexible demand at the neighborhood level. We carried out a thorough assessment of distribution grid quality of supply, which shows that the market we propose together with appropriate incentives achieves considerable reductions on the excess of renewable energy production towards Medium Voltage, reaching reductions of above 30% in relevant cases. A key consequence of synchronizing local production with demand flexibility is that we obtain important reductions of the peak power flowing through the transformer, which can be above 10% in relevant cases. An additional benefit is the reduction of losses on both the transformer and the lines. Moreover, the fact of locally balancing the excess of renewable energy production reduces the possible negative impacts of massive deployment of renewable energy sources on the global grid.

The results of Chapter 4 confirm that the local energy market we have proposed increases the capacity of distribution grids for hosting renewable energy sources. Nevertheless, as most scheduling mechanisms, the market creates further imbalances in flows across phases, which favor higher voltage rises/drops and neutral losses. In Chapter 5, we propose to dynamically allocate households to phases to cope with these issues by coordinating phase switching decisions with market decisions. The architecture allows for a progressive deployment of dynamic phase switches, which can be coupled to the progressive penetration of Distributed Energy Resources. We show that, for a scenario with 50 households where 80% of them are equipped with Photovoltaic panels and 60% with storage, only a small set of households (6%) need to be equipped with solid state switches to counteract the negative effects of scheduling mechanisms while maintaining all their benefits.

In addition we have shown that combining the local market proposed in Chapter 4 with Dynamic Phase Switching we can exploit all the benefits of the former and considerably improve the capacity of distribution grids for hosting renewable energy sources in terms of voltage deviations, neutral losses and network unbalance; for example, we have shown that, by deploying switches in 12% of total houses, voltage deviation levels can be reduced despite almost doubling the amount of renewables (e.g. from 25 to 40 houses equipped with Photovoltaic panels) and the Voltage Unbalance Factor levels remain similar to the ones observed on a setting without Distributed Energy Resources.

In the last two chapters we made the hypothesis that load and production forecasts were perfect. Nevertheless, as all ex-ante mechanisms, local energy market schedules rely on (hour-ahead) forecasts whose accuracy may be low, which can seriously impact their performance. In order to

face this issue, in Chapter 6 we propose a game-based real-time control mechanism that copes with forecast errors by driving households to a final exchange with the grid that favors the enforcement of market transactions while taking into account distribution grid constraints. The proposed game has an aggregative equilibrium that can be attained in a number of iterations independent of the amount of households, which makes the overall approach of this thesis entirely scalable. We evaluated the performance of the mechanism for a scenario with 50 households, where 80% of them are equipped with Photovoltaic panels and 60% with storage. As expected, under the hypothesis of hour-ahead persistence forecast, the simulations show that without a real-time coordination mechanism the grid would not be capable of hosting such level of penetration of renewable energies. However, when the real time control mechanism is applied the violations of thermal constraints can be entirely eliminated, thanks to peak reductions of flow intensity of 16%, and the average voltage variations are consistently reduced, reaching peak reductions of around 20%. Such voltage deviation reductions are achieved by combining the real time control mechanism with dynamic phase switching. We show that the proposed real-time mechanism is capable of coping with hour-ahead forecast errors by adjusting the flows issued from local market commitments towards an equilibrium that optimizes prosumers' electricity bill while significantly improving distribution grid reliability and quality of supply.

In summary, this thesis presents a general architecture that achieves the goal of facilitating the development of innovative services for customers, by enabling them to become prosumers playing a key role on the support of the energy transition, through the exchange of energy and flexibility services with neighbors, service providers and network operators. In particular, we propose three complementary demand side management mechanisms that support novel energy services, enabling prosumers to reduce their electricity bill by sharing renewable energy among their neighbors on an hour-ahead local market and by participating to a real-time reserve for the Distribution System Operator. The combination of the proposed local energy market, dynamic phase switching and game-based real-time control mechanisms provide solutions for major distribution grid challenges without requiring important infrastructure investments, allowing to attain the objectives of the thesis related to effectively increasing the capacity of distribution grid for hosting renewable energy and supporting the energy transition.

Finally, the proposed general architecture and novel energy services with its corresponding Demand Side Management mechanisms also represent the base for future innovations in terms of energy management systems and related energy services.

2 Future work

We briefly outline possible future research directions, including possible future innovations enabled by the proposed architecture and mechanisms. First we will describe the research directions directly related to the thesis work followed by possible research directions for future energy systems.

2.1 Extensions for additional value creation

2.1.1 Extensions to the smart home architecture

In Chapter 2 we presented a general IoT-based Smart Home architecture, enabling the distribution of intelligence towards the edge and the interoperability among devices from heterogeneous domains (health, energy, security, etc.). The lack of orchestration/federation mechanisms needed to provide conflict resolution, distributed agreements and enforcement of security of transactions in such a distributed environment should be addressed by an extension of the architecture. In addition, the transactive functionalities of such an architecture can enable new business models thanks to

novel interactions among actors or new ways of exploiting sensor data, which need to be thoroughly analyzed.

Orchestration of services - The IoT paradigm aims to extract value from novel interactions among people, objects and services from different domains. This goal has been hindered by siloed ecosystems that fail to interoperate. There are middlewares, such as IoTivity from Open Interconnectivity Foundation, that have the potential for breaking those silos, enabling devices from different manufacturers offering services in different domains to seamlessly communicate and provide value to users. The interoperability at device level together with the distribution of intelligence towards the edge will raise conflicts among controllers from different domains for their access to actuators or user interactions. Thus, the autonomous orchestration of distributed smart devices becomes one of the main challenges for achieving the IoT promise. This orchestration of services from different domains has been explored experimentally at the scope of a household during the thesis, but due to limitations of time and lack of maturity of state of the art technologies, our effort was focused on the integration of households to the neighborhood transactive platform. Technology is rapidly evolving towards enabling the integration of IoT devices with distributed ledger technologies[1], which would allow for an experimental and theoretical analysis of the resolution of conflicts among controllers of different domains.

Business models enabling interoperable distributed platforms - The use of game theory to model interactions among IoT actors for sensing applications has been proposed by Luis Guijarro [6]. The extension of such models to the Smart Home is an interesting subject for future research.

2.1.2 Distribution grids energy management architecture extensions.

In Chapter 3 we proposed a distribution grid energy management architecture, in which we introduced two novel concepts: The virtualization of distribution grid infrastructure and the blockchain-based transactive platform. Both concepts offer plenty of matter for future research, from which we present some examples in the following paragraphs.

Virtual Distribution Grids - Virtual Distribution Grids were proposed in Chapter 3 for the overall energy management of distribution grids, inspired by network slicing mechanisms usually applied to data networks. In Demand Side Management literature we can find interesting results for the optimal control of Electric Vehicle charging, of residential prosumers in a Microgrid, or for commercial/industrial prosumers. The problem is that all those resources share the same distribution grid and Demand Side Management mechanisms proposed for their simultaneous control are generally non tractable or take simplifying assumptions that make the results inapplicable. Future work should evaluate the specific technical constraints (notably shared voltage across virtual distribution grids) imposed by the electricity grids for the virtualization of the infrastructure. If the constraints can be satisfied then a whole set of mechanisms designed for data networks, could potentially be applied to improve the allocation of resources in electricity networks.

Design of economic aspects of a transactive platform - There are several economic aspects of the proposed blockchain based platform that would need further study. For instance, the conditions of issuance of coins/certificates/Points in exchange of balancing local renewable production need to be addressed. This could be done through a cryptocurrency approach which would led us to define the initial issuance and distribution, the exchange with respect to other coins, as well as constraints

[1] Filament (https://filament.com/) and IOTA (https://iota.org/) are two relevant examples.

on its future value (inflationary vs deflationary), etc. Another approach could be to create discount codes that would be collected back by electricity suppliers whenever they are used and exchanged by money at a rate proportional to the value created to the grid when the token was issued. Another economic aspect that should be analyzed is the right economic incentives for people to participate on the platform to exchange services and the business models for the different parties involved.

2.1.3 Extending local renewable energy market results

The local renewable energy market proposed in Chapter 4 can be extended in several directions:

- Consider flexible appliances. This can start by determining the potential of such flexibility by modeling flexible appliances as small batteries.
- Consider Shared batteries controlled by the Distribution System Operator or a third party.
- Include Electric Vehicles in the optimization model of households and on the market by enabling the trading outside sun hours, with Electric Vehicles becoming the sources of renewable energy charged during sun hours.
- Consider several Utilities providing different prices, as well as the possibility of choosing dynamically which will provide/absorb the energy not transacted with neighbors.
- Include aggregators offers for flexibility on the mix. These last two aspects would require the extension of the trading agent towards the implementation of smart mechanisms to decide the allocation of the flexibility budget.
- Model the fact that Utilities and aggregators chose their prices strategically, knowing that households can exchange energy with each other. To model such a system where different types of atomic and non-atomic agents compete for resources, game theory results such as "A mixed Optimum in Symmetric Distributed Computer systems" [101] could be analyzed.
- The scalability of the local energy market approach as well as the robustness to different parameters also needs further work.

Evaluation of other auction mechanisms Additional auction mechanisms could be evaluated and compared, with the limitation on the properties of such mechanisms by the impossibility results that we cannot have simultaneously Strategy proofness, Efficiency and Budget balance. On the thesis we choose a mechanism that sacrifices in efficiency for asymptotic efficiency, but other approaches can be followed; notably relaxing strategy proofness and studying the existence of dominant strategies and dynamic mechanisms to attain the corresponding equilibriums.

Price incentives for synchronizing demand and production peaks - The heuristic approach followed on the thesis for defining pricing incentives to synchronize demand and production peaks was useful to demonstrate the potential of local markets for balancing local renewable energy with flexible demand. Nevertheless, finding the optimal incentives taking into account the possible auction mechanisms is a subject of future work.

2.1.4 Improvements to the Real time control mechanism

The solid performance of the real-time market mechanism presented in Chapter 6 for reducing peak current flows and voltage deviations can be further improved by better selecting the parameters of the dynamic control scheme and of the local cost functions. With respect to the combination with the dynamic phase switching approach, the selection of households and the switching mechanism could be specifically adapted for further reducing voltage deviations. We are currently working on a sensibility analysis to very short term load/production forecast errors that could provide valuable insights for the development of stochastic game models.

Apply Rosen results for the real time control of energy flows on a distribution grid - Determine if the problem of real time control of energy flows respects Diagonal Strict Concavity for applying Rosen's Normalized Nash equilibrium concept and dynamic mechanisms. The interest of such mechanisms would be that the aggregative constraints are respected in all the iterations towards equilibrium and that the price signal is the same for all the agents regardless of the phase or the point in the feeder where they are connected.

Stochastic models - Consider stochastic aspects of both renewable energy production and demand in the design of Market mechanisms, Phase Switching algorithms and Real time control of flows in a distribution grid. Notably Stochastic Game Theory models could potentially be applied for the real time control of flows.

2.2 Future electricity distribution grids

Over the basis of the extensions described before, we will provide the elements necessary to enable our vision of future electricity distribution grids.

During our work we focused on providing mechanisms for the local balancing of renewable energy production and consumption, by providing a transactional architecture based on blockchain technology. In future distribution grids, transactional architectures have the potential to enable the energy domain to move from selling electrons to selling differentiated energy services, with different quality of service (for instance in the event of a congested grid), with a more dynamic choice of supplier, with a specific choice of sources of energy and with a mobility that would allow to consume personalized energy services and share energy resources regardless of location.

Such architectures should enable the exchange of energy services beyond local balancing, as well as other type of services beyond energy. Among the energy services that can be envisaged, are the provision of ancillary services for the transmission system operator, such as frequency regulation or reactive power and voltage control. For instance, aggregators and other service providers could compete on local markets for flexibility resources provided by households or electric vehicles, which then will be aggregated and exchanged on the wholesale market. The mechanisms to enable this services as well as the coordination of the usage of flexibility for local and global purposes are a subject of further research, in particular for the stability and reliability of the grid under such complex and correlated mechanisms, particularly if the possibility of islanding of distribution grids is considered.

2.2.1 Smart Home - Smart City interoperation

Determine the mechanisms by which a distributed interoperable smart home platform can interact with a distributed smart city platform for the exchange of information, transactions and services.

2.2.2 Orchestration of services and their access to constrained resources

A transactive architecture that supports services from different domains can bring a huge set of opportunities, but it is not without challenges. A shared transparent transactive platform could certainly facilitate the creation, coordination and auditing of such interdomain services. The orchestration of different services, their interaction with constrained resources and the enforcing of customer policies in such a context seems at most challenging.

2.2.3 Mobility as a key enabler of innovative (energy) services

One of the distinct features of the local energy exchange proposed on the thesis is the reward of all those who participate in locally balancing renewable energy production. This reward may take the form of a digital coin or bonus points that could then be used in exchange of energy services. Mobility appears as one of the major vectors of innovation as this energy related coin could be used to seamlessly access personalized energy services regardless of location. Examples of the ubiquitous usage of electricity are to charge your electric car in the house of a friend and pay using your account or take public transport powered by electricity using locally earned points/coins. Sharing economy services of the like of Blockcharge (Slock.it and RWE) can also be envisaged. Mobility related services require the possibility of using the coins outside the neighborhood and thus outside the local blockchain, which poses several challenges in terms of scalability, security and trust. A hierarchical permissioned blockchain dedicated to orchestration across local ones could provide a solution to such mobility needs. Additionally, in order to exploit the potential value of interoperability across blockchain technologies we could consider solutions based on:

- Existing public blockchains (Bitcoin, Ethereum)
- Sidechain protocols such as Blockstream or more recently Cosmos, which provide a network of distributed ledgers

2.2.4 Governance

The choice of blockchain technology to power a transactive platform was strongly motivated by the potential extensibility to services other than energy. Part of this potential is given by the flexibility in governance mechanisms. The mechanisms through which a consortium of service providers from different domains could achieve agreement are certainly a subject for further analysis.

2.2.5 Privacy

One of the main properties of blockchain technology is transparency which makes it hard to ensure privacy of transactions. During the thesis we rely on the fact that the energy domain counts already with a trusted party, which is the Distribution System Operator, with all the controls in place from the CNIL and the CRE for ensuring the privacy of consumers' data. For domains without such an actor/ecosystem, or if we would like to eliminate/substitute the trust on a third party with some distributed mechanisms, there is still research work to be done. There are some proposed solutions for example based on zero-knowledge proofs like Zcash, but each solution has its limitations.

2.2.6 Security

Each one of the existing blockchain designs has trade-offs between security and scalability. There have been mayor security issues even with most popular implementations of blockchain technology. All the solutions have some drawbacks or are potentially vulnerable to some attack vectors. A throughout

analysis on the security guaranties provided by each technology is extremely important but it has not yet been done.

2.2.7 Blockchain base services

In a similar way there are services like Domain Name System, Certificate authorities, Content Distribution Networks, etc. The blockchain ecosystem has yet to develop plenty of services that will exploit the transparency of distributed ledgers to provide monitoring, registries, reputation systems, privacy transactions, content curation, legal services, etc.

Acronyms

AMI Advanced Metering Infrastructure.

API Application Programming Interface.

BBB BeagleBone Black.

BLE Bluetooth Low Energy.

BRE Balancing Responsible Entities.

CIM Common Information Model.

CF *Cloud Functions*.

CoAP Constrained Application Protocol.

CBOR Concise Binary Object Representation.

DDS Data Distribution Service.

DER Distributed Energy Resources.

DNS Domain Name System.

DNS-SD Domain Name System (DNS) Service Discovery.

DPS Dynamic Phase Switching.

DR Demand Response.

DSM Demand Side Management.

DSO Distribution System Operator.

DTLS Datagram Transport Layer Security.

ECA Event-Condition-Action.

EF *Edge Functions*.

EMS Energy Management System.

EV Electric Vehicles.

EXI Efficient eXtensible Markup Language (XML) Interchange.

FIT Feed In Tariff.

HAF Highest Average Flow

HAN Home Area Network.

HEMS Home Energy Management System (EMS).

HTTP Hypertext Transfer Protocol.

ICT Information and Communication Technologies.

IoT Internet of Things.

IP Internet Protocol.

IPv6 Internet Protocol version 6.

6LowPAN IPv6 over Low power Wireless Personal Area Networks.

JSON JavaScript Object Notation.

LAN Local Area Network.

LCOE Levelized Cost of Electricity.

LV Low Voltage.

M2M Machine to Machine.

MV Medium Voltage.

MB Mean-based.

mDNS multicast DNS.

MQTT Message Queue Telemetry Transport.

MDA Multi-unit Double Auction.

NFC Near Field Communication.

NGF *Networking Gateway Functions*.

OIC Open Interconnect Consortium.

OLTC On-Load Tap Changer.

OS Operating Systems.

PAR Peak to Average Ratio.

PCC Point of Common Coupling.

PoS Proof of Stake.

PoW Proof of Work.

PV PhotoVoltaic.

QoS Quality of Service.

RTC Real-Time Control.

RES Renewable Energy Sources.

RESTful REpresentational State Transfer.

RFID Radio Frequency Identification.

SCADA Supervisory Control And Data Acquisition.

SEP 2.0 Smart Energy Profile.

SOAP Simple Object Access Protocol.

SoC State of Charge.

STS Solid-state Transfer Switches

TCP Transmission Control Protocol.

TOU Time Of Use.

TSO Transmission System Operator.

UDP User Datagram Protocol.

UPnP Universal Plug and Play.

UI User Interaction.

VDG *Virtual Distribution Grids*.

VLAN Virtual Local Area Network (LAN).

VPP Virtual Power Plants.

VUF Voltage Unbalance Factor

WAN Wide Area Network.

XML eXtensible Markup Language.

XMPP extensible Messaging and Presence Protocol.

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Paradigmes et architectures innovantes pour l'avenir des réseaux électriques de distribution soutenant la transition énergétique

Jose Horta

RESUME :

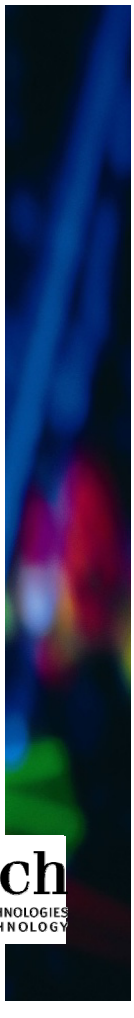
Les futurs réseaux de distribution d'électricité devront héberger une part importante et croissante de sources d'énergies renouvelables intermittentes. De plus, ils devront faire face à des nouvelles variations des courbes de charge, dues notamment à une part croissante de véhicules électriques. Ces tendances induisent le besoin de nouveaux paradigmes et architectures d'exploitation du réseau de distribution, afin de fiabiliser les réseaux et assurer la qualité de fourniture d'électricité. Par ailleurs, ces nouveaux paradigmes vont permettre le développement des services innovants.

D'un côté, les gestionnaires de réseau s'appuieront de plus en plus sur des flexibilités fournies par des ressources énergétiques distribuées (flexibilités de consommation, stockage électrique, modulation des sources d'énergie) à cause de son potentiellement meilleur rapport coût-efficacité par rapport au renforcement des infrastructures. D'un autre côté, les consommateurs deviendront progressivement des prosumers (acteurs de leur consommation d'énergie) qui joueront un rôle actif dans la gestion de l'énergie des réseaux intelligents, en exploitant la flexibilité de certaines des équipements de leur logement (appareils électroménagers, batteries et panneaux solaires) pour moduler leur courbe de charge. L'Internet des Objets est un outil essentiel pour permettre aux logements de jouer un rôle actif, car il a poussé une nouvelle vague d'appareils connectés à la Smart Home et de services associés, dont le domaine de l'énergie peut devenir l'une des principales applications.

Dans cette thèse nous proposons une nouvelle architecture capable de favoriser la collaboration entre les acteurs du marché de gros, les gestionnaires de réseau de distribution et les clients finaux, afin de tirer parti des ressources énergétiques distribuées tout en prenant en compte les contraintes des réseaux de distribution. L'architecture est conçue pour fournir des services innovants de gestion de la demande résidentielle, avec un focus particulier sur les services liés à l'autoconsommation individuelle (au niveau d'un logement) et collective (à l'échelle d'un quartier). Dans le cadre de ces objectifs généraux, la thèse apporte trois contributions principales. D'abord, sur la base de l'Internet des Objets et de la technologie blockchain, la thèse fournit les éléments de base pour les futures architectures de gestion de l'énergie au niveau du réseau de distribution. Ensuite, en focalisant sur les services rendus par de telles architectures, nous proposons un marché intra-journalier au pas horaire pour l'échange local de l'énergie renouvelable entre les logements, associé à un mécanisme d'allocation dynamique des phases afin d'améliorer la qualité de fourniture d'électricité. Finalement, nous proposons un mécanisme de contrôle en temps réel pour l'ajustement des transactions du marché vers des échanges finaux d'électricité qui respectent les restrictions posées par le gestionnaire du réseau électrique.

L'architecture et les mécanismes de gestion de la demande proposés visent à réduire les transits et les pertes et, par conséquent, à augmenter la capacité d'accueil des sources d'énergie renouvelables sur les réseaux de distribution basse tension. Les performances sont évaluées à l'aide de simulations de load flow basées sur des profils de charge réalistes. Elles fournissent des éléments utiles à la conception des futurs systèmes de gestion des réseaux de distribution.

MOTS-CLEFS: Gestion active de la demande, réseau électrique intelligent, Internet des Objets, Mécanismes d'enchères, Théorie de Jeux



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Innovative paradigms and architectures for future distribution electricity networks supporting the energy transition

Jose Horta

ABSTRACT:

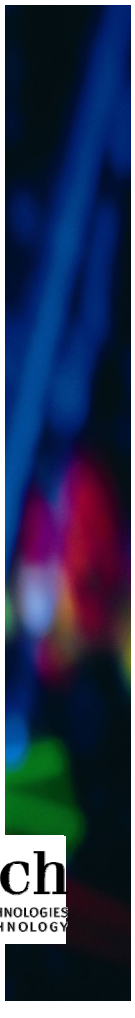
Future electricity distribution grids will host an important and growing share of variable renewable energy sources and local storage resources. Moreover, they will face new load structures due for example to the growth of the electric vehicle market. These trends raise the need for new distribution grid architecture and operation paradigms to keep the grid stable and to ensure quality of supply. In addition, these new paradigms will enable the provision of advanced new services.

On the one hand, distribution System Operators will increasingly rely on demand side flexibility provided by distributed energy resources (such as flexible loads, storage resources and controllable distributed energy sources) due to their adaptability and potential cost-effectiveness compared to traditional infrastructure reinforcements. On the other hand, households will progressively become prosumers playing an active role on smart grid energy management by exploiting flexibility potential of household devices that consume, store or produce electricity. The Internet of Things is a main enabler for households to play an active role, as it has been pushing a new wave of Smart Home connected devices and related services, from which the energy domain can become one of the main business cases.

In this thesis we propose a novel architecture capable of fostering collaboration among wholesale market actors, Distribution System Operators and end customers, to leverage flexible distributed energy resources while respecting distribution system constrains. The architecture is designed for providing innovative Residential Demand Side Management services, with a special focus on services enabled by self-consumption at the household and neighborhood level. Following these general objectives, the thesis provides three main contributions. First, based on Internet of Things and blockchain technology, we propose the building blocks for future distribution grid energy management architectures. Then, focusing on the services enabled by such architectures, we propose hour-ahead markets for the local exchange of renewable energy among households together with dynamic phase allocation mechanism to improve the quality of electricity supply. Finally, we propose a real time control mechanism for the adjustment of market decisions to satisfy Distribution System Operator constraints.

The architecture and demand side management mechanisms proposed in this thesis have the potential to alleviate congestion, reduce voltage deviations and losses, and consequently augment distribution grid capacity for hosting renewable energy sources. We evaluate such potential through comprehensive simulations using power flow analysis and realistic load profiles, providing valuable insight for the design of future distribution grid architectures and energy management systems.

KEY-WORDS: Demand Side Management, Smart Grids, Internet of Things, Market Mechanisms, Game Theory



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