RES4AFRICA FOUNDATION

DEPLOYING BATTERY ENERGY STORAGE SOLUTIONS in Tunisia

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AMA	Asset Management Agreement
AC	Alternating Current
ANME	Agence nationale de maitrise de l’énergie
BESS	Battery Energy Storage System
BMS	Battery Management System
BNEF	Bloomberg New Energy Finance
BoP	Balance of Plant
CC	Combined Cycle
COD	Commercial Operation Date
C&I	Commercial & Industrial
CTER	Technical Commission of private renewable power generation
DC	Direct Current
DNO	Distribution Network Operator
DoD	Depth of Discharge
EMC	Electromagnetic Compatibility
EPC	Engineering, Procurement, Construction
ERV	Variable Renewable Energy
FCAS	Frequency Control Ancillary Services
FIT	Feed-In Tariff
GT	Gas Turbine
IEA	International Energy Agency
KPI	Key Performance Indicator
LCOES	Levelized Cost of Energy Storage
LFP	Lithium Iron Phosphate
Li-ion	Lithium Ion
LMO	Lithium Manganese Oxide
LV	Low voltage
MTOE	Mega tonne of oil equivalent
MV	Medium voltage
NOEM	National Observatory for Energy and Mines
Na-ion	Sodium Ion
NMC	Lithium Nickel Manganese Cobalt Oxide
OEM	Original Equipment Manufacturer
OEYA	Operational Energy Yield Assessment
O&M	Operation and Maintenance
OPEX	Operational Expenditure
PPA	Power Purchase Agreement
PCS	Power Conversion System
PV	Photovoltaic
REDOX	Reduction and Oxidation
RFB	Redox Flow Battery
RINA	RINA Tech UK Ltd
RTE	Round Trip Efficiency
SCADA	Supervisory Control and Data Acquisition
SoC	State of Charge
SoH	State of Health
SPV	Special Purpose Vehicle
STEG	Tunisian Company of Electricity and Gas

STEP	Energy Transfer System by Pumping Turbinage
UPS	Uninterruptable Power Supply
UTICA	Tunisian Union of Industry, Commerce and Handicrafts
VFB	Vanadium Flow Battery
WT	Wind Turbine
WWTP	Wastewater Treatment Plant

Foreword

The world is currently facing its first truly global energy crisis, brought about by the Russia-Ukraine crisis. Its impact is far-reaching, disrupting global energy supply and demand patterns, fracturing long-standing trading relationships, and affecting all countries.

It is important to dispel some of the mistaken and misleading ideas about this energy crisis, such as the belief that it is a clean energy crisis when, in fact, the world is struggling with too little clean energy. Faster clean energy transitions would have helped to moderate the impact of this crisis, and they represent the best way out of it. Another mistaken idea is that this crisis is a setback for efforts to tackle climate change. In fact, it can be a turning point towards a cleaner and more secure energy system, thanks to the unprecedented response from governments around the world, as registered by the IEA in the Stated Policies Scenario (SPS), the Announced Pledges Scenario (APS) and the foreseen Net Zero Emission Scenario (NZE).

In the NZE Scenario, the IEA predicts that almost 90% of global electricity generation in 2050 comes from renewable sources, with solar PV and wind together accounting for nearly 70%. The integration of these variable energy sources into national energy grids will largely depend on storage technologies, and among them especially batteries, to provide the flexibility required to smooth the energy supply which expected to reach 3,100 GW in installed capacity. Locally, all countries will see a revolutionised energy sector, and especially those who have not still exploited their renewable energy potential, such as Tunisia.

The objective of this report is to look into the potential of Battery Energy Storage System (BESS) development in Tunisia, in line with national efforts towards a clean and sustainable energy transition as well as ensuring the optimal use of energy sources and improving energy security. This report is divided into two parts: The first looks into the technical aspect of the BESS, uses and applications building on international experience and lessons learned. The second part elaborates on the current situation of the energy mix and renewable energy sector in Tunisia to identify enabling measures to unlock the BESS market in the country.

Roberto Vigotti, Secretary General RES4Africa Foundation

Résumé Exécutif

Stockage d'énergie par batterie (BESS), pilier des futurs systèmes énergétiques

La technologie de stockage d'énergie par batterie (BESS) est une tendance mondiale d'aujourd'hui. Au cours de ces dernières années, cette technologie a été un facteur clé pour la distribution d'énergie décarbonée, offrant un service rapide d'électricité aux consommateurs industriels, commerciaux et résidentiels. Des solutions technologiques avancées telles que le lissage des pics de consommation et l'équilibrage de la charge dans les projets BESS en Europe et en Australie ont permis de révolutionner le système d'équilibrage du réseau, entraînant ainsi des prix de l'énergie plus bas pour les consommateurs et une amélioration des émissions de carbone.

L'utilisation de la BESS est largement considérée comme cruciale pour la sécurité et la fiabilité énergétiques futures. Le déploiement de cette technologie peut offrir une multitude de services et d'avantages tels que des économies pour les consommateurs, une réduction des émissions de carbone, une réduction et équilibrage de la variabilité et la limitation des énergies renouvelables, facilitation de l'intégration au réseau tout en garantissant un approvisionnement adéquat en électricité. Cette technologie devrait être promue par les décideurs et des programmes de soutien aux particuliers et aux entreprises souhaitant investir dans cette technologie.

Le chapitre 4 de ce rapport fournit un aperçu des technologies de batteries les plus avancées sur le marché et évalue chacune d'entre elles en fonction de ses attributs de performance clés. Les trois technologies de batterie les plus avancées sur le marché sont les batteries lithium-ion, les batteries au plomb et les batteries de flux redox. Ensuite, plusieurs aspects liés à l'utilisation des systèmes de stockage d'énergie par batterie (BESS) sont présentés.

Tout d'abord, différents types de BESS sont nécessaires pour couvrir les demandes en énergie et les services auxiliaires à court et long terme, tels que la régulation de la fréquence, la stabilisation de la tension, le lissage de la puissance, etc. et résolvent également les problèmes liés aux déséquilibres dans le réseau électrique et les batteries Li-ion sont utilisées pour leur temps de réaction rapide et leur densité d'énergie élevée. Les systèmes Li-ion ont typiquement des durées de 0,5 à 8 heures. Les services de stockage à long terme visent à stocker de grandes quantités d'énergie pour améliorer l'efficacité et l'économie du réseau électrique. Les systèmes Li-ion peuvent encore être utilisés, mais les systèmes à base de vanadium redox seront en principe plus compétitifs en coût pour les durées plus longues même si cela n'a pas encore été démontré à grande échelle car la technologie n'est pas encore suffisamment mature (et le besoin de stockage au-delà de 8 heures est encore assez rare). Les systèmes à base de vanadium redox ont typiquement des durées de 3 à 12 heures mais nécessitent plus d'espace par kWh que les systèmes Li-ion en raison de leur faible ratio énergie-volume.

Ensuite, les batteries ont des risques de sécurité liés à leur utilisation en dehors de leurs conditions recommandées, comme les surcharges, les chocs mécaniques ou les incendies. Les risques de défaillance peuvent être évités en utilisant un système de gestion de batterie (BMS), en espaçant les unités de batterie appropriées, en installant des systèmes de suppression d'incendie et en prévoyant des procédures de sécurité en cas d'urgence. Enfin, la dégradation des batteries peut être physique ou chimique, et doit être surveillée pour identifier les effets surtout sur la capacité.

Les différents composants nécessaires au bon fonctionnement d'une centrale de stockage d'énergie (BESS) incluent :

- Les conteneurs de stockage,
- Les modules de batterie,
- Les systèmes de climatisation,
- Les systèmes de suppression d'incendie,
- Les systèmes de gestion de batterie,
- Les systèmes de conversion d'énergie,
- Les transformateurs,
- Les systèmes de commutation et de contrôle et de surveillance (SCADA).
- L'équilibre civil et électrique de l'installation
- La connexion au réseau.

Le système de conversion d'énergie (PCS) est un élément clé pour contrôler le flux d'énergie électrique dans le système. Les transformateurs permettent d'adapter la tension de sortie du PCS à la tension du réseau électrique et offrent une isolation galvanique. Les systèmes de commutation permettent de gérer les équipements électriques. Les systèmes de contrôle et de surveillance tels que le SCADA permettent de surveiller et de contrôler les performances de la BESS.
Les principaux acteurs impliqués dans l'intégration des systèmes de stockage d'énergie (BESS) sont:

- Les fournisseurs (ou fabricants d'équipement d'origine) qui produisent des cellules de batterie
- Les intégrateurs (ou vendeurs) qui offrent les services requis pour mettre en œuvre des projets BESS.

Les principaux fournisseurs de batteries pour BESS sont des grandes entreprises qui ont la capacité de produire des batteries de haute qualité pour des projets de grande envergure. Les intégrateurs BESS sont également présentés et classés selon leur capitalisation boursière actuelle. Le chiffre d'affaires du groupe représente le revenu total généré par l'entité grâce à la vente de services ou de produits aux consommateurs.

Le déploiement de stockage d'énergie stationnaire peut être divisé en deux types d'applications de marché : les applications front-of-meter (FTM) et les applications behind-the-meter (BTM). Les FTM sont des batteries de stockage d'énergie de grande échelle généralement connectées aux lignes de distribution/transmission ou aux actifs de production d'électricité. Elles fournissent des services aux opérateurs de réseau tels que les services auxiliaires ou le soulagement de charge du réseau tandis que les BTM sont de petites batteries de stockage d'énergie utilisées pour les clients commerciaux, industriels et résidentiels. Elles peuvent être utilisée pour l'optimisation et la gestion de la demande, pour maximiser la consommation des EnRs colocalisées, pour fournir une alimentation de secours en cas de coupure de courant et un soutien de fréquence et de tension pour le réseau. Bien que le marché soit actuellement dominé par les batteries de grande échelle (FTM), on s'attend à une augmentation des batteries de petite échelle (BTM) d'ici 2030.

Les systèmes de stockage d'énergie BESS peuvent être connectés au réseau de deux manières différentes : de manière autonome ou en co-localisation. L'application autonome consiste à connecter directement le BESS à un nœud du réseau, sans nécessairement être à proximité d'une source d'énergie renouvelable, dans le but de fournir des services au réseau pour améliorer sa stabilité et sa qualité. Dans une application de co-localisation, le BESS est installé à proximité immédiate d'une source d'énergie renouvelable intermittente (comme une ferme solaire ou éolienne), afin de promouvoir l'interaction entre les deux actifs et de permettre le partage de certains composants BoP.

Les stratégies opérationnelles des deux actifs sont souvent liées et axées sur l'optimisation de l'utilisation de l'énergie produite par la source d'énergie renouvelable, par exemple en favorisant la récupération de la coupe, la récupération de la limitation et le décalage horaire. Les plantes de co-localisation peuvent être subdivisées en deux catégories macro, en fonction de la position de la connexion BESS : en couplage AC ou en couplage DC. La Section 2.1 de la Partie 1 de ce rapport décrit ces connexions plus en détail, en mettant en évidence les avantages et les inconvénients de chaque application.

La Tunisie entre défis et relance

La Tunisie connaît une situation énergétique marquée par des ressources énergétiques primaires limitées, une diminution de la production d'énergie et une augmentation de la demande nationale d'énergie. Les ressources en énergie primaire ont atteint 3,9 MTep fin octobre 2022, enregistrant une baisse de 8 % par rapport à la même période de l'année précédente, principalement due à la diminution de la production nationale de pétrole brut. La demande en énergie primaire s'est stabilisée au même niveau entre fin octobre 2021 et fin octobre 2022, à 8 MTep. Cet écart entre la production d'énergie et la demande nationale d'énergie représente un déficit de 4,1 MTep fin octobre 2022, contre un déficit de 3,7 MTep fin octobre 2021. Ce déficit énergétique pourrait représenter 95% de la demande d'ici 2035 si les ressources nationales et la demande énergétique continuent de suivre la même tendance actuelle. Ceci poserait un risque de soutenabilité économique et financière du secteur énergétique, mais aussi avec des conséquences sociales et environnementales pour le pays.

Le taux d'indépendance énergétique, qui représente le rapport entre les ressources énergétiques primaires et la consommation primaire, s'est établi à 49 % fin octobre 2022, contre 53 % fin octobre

2021. Bien que la Tunisie ait adopté une diversification du mix énergétique depuis 2004, elle est encore largement dominée par les combustibles fossiles, une grande partie étant importée. Ces combustibles sont utilisés pour produire environ 96 % de l'électricité générée en Tunisie, laissant seulement 4,1 % (2021) d'électricité produite à partir de sources d'énergie renouvelable. Il est important de mentionner que le pourcentage de 4,1 % de renouvelables est la valeur prenant en compte la production des toits (secteur résidentiel + industriel). Les centrales solaires, éolienne et hydrauliques à grande échelle contribuent de manière limitée à hauteur de 1,8 % de la production nationale.

Afin d’accélérer la transition énergétique, la Tunisie a adopté un plan ambitieux en matière d'efficacité énergétique et d'utilisation des énergies renouvelables, avec un objectif d’atteindre une part de 30% d'énergies renouvelables dans le mix énergétique à l’horizon 2030. La nouvelle stratégie énergétique à l’horizon 2035, adoptée en Avril 2023, a fixé un nouvel objectif d’installer une capacité d’énergies renouvelables de 8530 MW d’ici 2035 pour la production d’électricité. Par ailleurs, la stratégie vise également à une transition énergétique juste ayant comme leviers la sécurité énergétique, la décarbonation de l’économie, ainsi que le développement économique inclusif.

En outre, depuis 2015, la Tunisie a opté pour un dispositif juridique et réglementaire renforcé dans le but de tirer le meilleur profit des énergies renouvelables, en particulier l’énergie solaire. La loi relative à la production d’électricité à partir d’énergies renouvelables a été adoptée en mai 2015 (Loi n° 2015-12 du 11 mai 2015). Conformément à la loi, il existe les trois régimes suivants applicables au développement des ressources énergétiques renouvelables avec participation privée:

- Régime de l'autoconsommation
- Régime des autorisations
- Régime des concessions

Pour atteindre des parts plus élevées d’énergies renouvelables dans le mix électrique, et réussir l’intégration d’énergies renouvelables variables comme l’éolien et le solaire dans le réseau électrique national, il est nécessaire de mettre en place un processus intégré de planification énergétique à long terme basée sur l’adoption des solutions tel que les solutions digitales (monitoring) et les technologies de stockage.

Recommandations pour une feuille de route pour l’introduction les technologies BESS en Tunisie

L’accélération de la transition énergétique en adoptant des technologies telles que les systèmes de stockage auront un impact important sur l'économie tunisienne, qui est actuellement fortement dépendante des combustibles fossiles importés. Les énergies renouvelables sont considérées comme un moteur clé pour une économie plus résiliente et capable de faire face aux fluctuations mondiales des matières premières. Cependant, pour atteindre cet objectif, il est nécessaire de construire un cadre réglementaire complet et stable, en accordant une attention particulière à la législation secondaire afin de la rendre pleinement et rapidement applicable.

Sur la base de l'analyse menée par le présent rapport, l'introduction des technologies BESS en Tunisie nécessite un plan d'action coordonné. Nos principales recommandations sont axées sur les trois piliers suivants.

Faciliter l'intégration des énergies renouvelables

Il est nécessaire de réviser les réglementations afin d'inciter au stockage par batteries, qui permet d'optimiser la production solaire et de fournir des services au réseau électrique. Pour cela, il serait important d'établir le stockage d'énergie comme une catégorie d'actifs distincte dans les réglementations futures et d'adopter des objectifs spécifiques pour le stockage dans les politiques énergétiques nationales. En outre, une législation intersectorielle pour le stockage, et une législation sur les tarifs horaires de consommation d'électricité (après la création d'une autorité de régulation indépendante) pourrait encourager les accords d'achat d'électricité (PPA) d'entreprises avec stockage. D'autres mesures parallèles pourraient être l'inclusion des systèmes BESS en tant qu'actifs éligibles dans les cadres de financement vert et dans les appels d'offre concurrentiels d'énergies renouvelables, ainsi que l'introduction de mesures incitatives telles que des incitations fiscales, des exemptions de droits de douane, une dépréciation accélérée et une participation du gouvernement à la propriété des technologies de stockage par batteries. En ce qui concerne les clients de la basse tension, et en accord avec la vision de la STEG, le passage du système de comptage net au système de facturation nette et déployer des compteurs intelligents favoriseront l'adoption de systèmes d'onduleurs hybrides pour le stockage distribué.

Faciliter l'exploitation et la gestion du réseau

Vu le potentiel des technologies BESS dans l'augmentation de l'efficacité, la flexibilité et la fiabilité des systèmes énergétiques, il serait opportun d'encourager l'opérateur de réseau à investir dans des systèmes de stockage d'énergie autonomes par batteries (comme dans le cas italien). Cela renforcerait le réseau électrique pour une intégration accrue des ressources énergétiques variables et distribuées, et permettrait l'adoption d'outils de flexibilité et de programmes de gestion de la demande.

Assurer le développement économique et la durabilité

Dans le cadre de l'introduction du Mécanisme d'Ajustement Carbone aux Frontières (CBAM) européen pour les exportations tunisiennes vers l'Europe, les systèmes BESS offrent une approche compatible avec la politique proposée. Les marchandises importées en Europe devraient avoir au moins 25% de l'énergie de fabrication provenant de sources renouvelables, ce qui renforcerait la dépendance vis-à-vis de l'énergie durable et des batteries. Par ailleurs, si une production de batteries venait à se développer en Tunisie à l'avenir, elle devrait être alignée sur le CBAM en termes de critères de durabilité. A cet égard, il serait important pour la Tunisie d'établir des normes de durabilité et de sécurité pour les technologies de batteries, et d'élaborer des programmes de sensibilisation et de développement de capacité à la fois pour les consommateurs et les fournisseurs. De plus, les normes techniques devraient être introduites dans le code des énergies renouvelables.

Recommandations pour le déploiement des BESS en Tunisie

Faciliter l'intégration des énergies renouvelables

- **Politiques et régulation**. Mettre en œuvre un cadre réglementaire complet qui inclut des objectifs et cibles spécifiques pour le stockage de l'énergie dans les politiques énergétiques nationales.
- **Structure du secteur**. Faire du stockage de l'énergie une catégorie d'actifs distincte des chaînes de valeur de la production, du transport et de la distribution dans le cadre de la future réglementation.
- **Prix**. Augmentation du prix de vente de l'électricité dans les contrats d'achat d'électricité (Power Purchase Agreements - PPAs) avec deux niveaux de prix, le niveau supérieur pour l'énergie fournie pendant les heures de pointe. Les projets dotés de capacités de stockage devraient maintenir leur compétitivité par rapport aux prix moyen : de 80 millimes à 270 millimes/kWh, incluant le prix du transport de l'électricité. Cela permettrait de générer des revenus supplémentaires grâce au transport de l'électricité.
- **Régime d'incitations**. Offrir des incitations fiscales, des exonérations de droits de douane, un amortissement accéléré et une participation de l'État au capital des technologies de stockage en batterie ; et soutenir l'inclusion des BESS en tant qu'actifs éligibles dans les cadres de financement verts.
- **Structure contractuelle**. Mettre en œuvre une législation intersectorielle pour le stockage de l'énergie dans le cadre des programmes d'EnR existants, qui définit les responsabilités en matière de propriété des services publics, des développeurs, des opérateurs et des régulateurs, et introduction d'une législation sur les tarifs en fonction de l'heure d'utilisation, inciterait les entreprises à conclure des PPAs avec stockage
- **Régime d'autoconsommation**. Permettre à une plus grande partie de la production d'énergie renouvelable d'être vendue dans le cadre du régime d'autoconsommation, de 30 % à 50 % de l'électricité totale produite.
- **Obligations**. Imposer une certaine capacité BESS (par exemple 10 %) dans les nouvelles centrales électriques et chez les consommateurs industriels dépassant un certain seuil.
- **Appels d'offre concurrentiels**. Mener des appels d'offre concurrentiels pour des portefeuilles de projets d'énergie renouvelable combinés à des actifs de stockage d'énergie afin de maximiser l'intégration des sources d'énergie renouvelables et de permettre aux preneurs

d'acheter de l'électricité qui peut être entièrement dispatchable et qui offre une meilleure stabilité.

- **Basse-tension**. Le système de facturation nette (net-metering) pourrait être révisé à mesure que la part des EnR dans le mix électrique devient substantielle. L'objectif est de s'assurer que le régime n'entrave pas l'intégration des systèmes de stockage d'énergie tout en continuant à fournir des incitations pour la production d'énergie renouvelable distribuée.

Faciliter l'exploitation et la gestion du réseau

Réseau Électrique. Encourager l'opérateur de réseau à investir dans des systèmes de stockage d'énergie autonomes par batteries (comme dans le cas italien). Cela renforcerait le réseau électrique pour une intégration accrue des ressources énergétiques variables et distribuées, et permettrait l'adoption d'outils de flexibilité et de programmes de gestion de la demande.

Assurer le développement économique et la durabilité

- **Mécanisme d'ajustement carbone aux frontières (CBAM).** Renforcer les exportations Tunisiennes vers l'UE en se conformant à l'exigence d'avoir au moins 25% de l'énergie de fabrication dérivée de sources renouvelables, ce qui signifie une plus grande dépendance à l'égard de l'énergie durable et des batteries.
- **Impact environnemental et sécurité.** Fixer des normes de durabilité et de sécurité pour les technologies des batteries : cela comprend des règles concernant l'approvisionnement en matériaux, le recyclage, la performance, la durabilité et les exigences de gestion en fin de vie.
- **Normes et standards techniques.** Introduire les normes techniques des BESS dans les cahiers des charges des appel d'offres et déterminer les normes environnementales qui fixeront la limite de puissance ainsi que les coûts du régime de concession dans les contrats BESS-PPA.
- **Monitoring.** Suivre l'évolution du marché BESS afin de mettre à jour périodiquement le cadre réglementaire pour les batteries : sur la base des tendances des coûts technologiques, des problèmes d'approvisionnement, des impératifs de l'économie circulaire et des objectifs plus larges de la transition énergétique.
- **Sensibilisation et développement de capacité**. Développer des programmes de sensibilisation et de renforcement des capacités: à la fois pour les consommateurs industriels sur les avantages du stockage de l'énergie et pour les fournisseurs sur les opportunités de marché.
- **Certification.** Certifier selon la norme internationale IEC 60086 relative aux batteries pour conformer les batteries aux critères de performance mondialement reconnus en matière de sécurité, de qualité et de fiabilité.
- **Fin de cycle de vie.** Créer un mécanisme pour la gestion des batteries après la fin de cycle de vie et anticiper les impacts environnementaux nuisibles du déclassement des systèmes de stockage de l'énergie.

PART 1. BATTERY ENERGY STORAGE SYSTEMS AND THEIR ROLE AS FLEXIBLE RESOURCES

1 BESS Technology

Battery Energy Storage System (BESS) deployment is a growing trend in today's energy market. In recent years, BESS has been a key enabler for decarbonised energy distribution, providing a quick response electricity service to industrial, commercial, and residential consumers. Advanced technological solutions such as peak shaving and load levelling in BESS projects in Europe and Australia have allowed BESS to revolutionise the grid balancing system subsequently leading to lower energy prices for consumers and improved carbon emissions. This form of energy storage is still undergoing many advancements to realise its full potential, most of which is being achieved from the development of diversified battery chemistries.

For energy markets, the use of BESS is widely considered to be critical for future energy security and reliability. The deployment of BESS can be seen to provide a multitude of services and benefits such as consumer savings, reduced carbon emissions, reduced curtailment of renewable energy, and meeting carbon emission targets.

1.1 Battery Types

This section provides an overview of current leading battery chemistries and evaluates each against key technical performance attributes. The three leading battery technologies on the market are lithium-ion batteries, lead acid batteries, and redox flow batteries.

Table 1: Key battery technical characteristics

Technology	Advantages	Disadvantages
Lithium-ion	• Cycle life of 3,000-12,000 • Fast response time • Fast deployment • Flexibility - suitable for a range of utility-scale applications • Original Equipment Manufacturers (OEM) available with commercial maturity • Lower volume and weight	• Thermal instability (runaway) • Optimal temperature range
Advanced lead acid	• Reliable and commercially mature • Many OEMs options available • Relative low cost • Low internal impedance • Broad range of available capacities • Fast deployment • Fast response • Able to produce very high currents	• Limited cycle life at high DoD • Large footprint required due to low energy density and low specific energy. • Must be charged relatively slowly due to potential for overheating.

		• Capacity reduces 50% with every 8°C increase from 25°C
Redox flow[1]	• Long cycle life (>20,000) • No capacity loss • Easy electrolyte swap • Flexibility (increase of capacity by addition of electrolyte tanks) • Insensitive to DoD • High safety (non-flammable, no thermal runaway)	• Limited number of projects deployed. • Limited OEMs available • Longer project deployment times • Toxicity of some electrolytes • Lower round trip efficiency • Higher auxiliary consumptions • Liquid electrolyte subject to risk of release to environment in case of leaks • Potential failure in case of impurities in liquid electrolyte • Larger footprint required due to lower energy density and lower specific energy.

The advantages and disadvantages of the market-leading battery technologies are summarised in Table 1, while in Table 2 a comparison of their Key Performance Indicators (KPI) is provided.

Table 2: Comparison of key performance indicators of different battery chemistries

Key performance indicators	Li-ion	Lead Acid	Redox Flow
Specific Energy (Wh/kg)	90–265	25–50	10–30
Energy Density (Wh/L)	160–370	50–100	15–35
Specific Power (W/kg)	150–400	75-200	50-110
RTE efficiency (%)	85–95	65-85	65–85
Cycle life (cycles)	3'000–12’000	<350	12’000-15’000
Cost (US$/kWh)	170-400	50-150	150-1’000
BESS Time duration (hours)	0.5-8	1-6	3-12
Safety requirements	Medium Fire risk	Low Flammable gases	Low Toxicity of electrolyte

[1] The most common type of batteries in this category is the Vanadium Redox Flow but there are also other experimental applications. As a consequence, in the following pages the report will make reference to this type of technology.

Green = Best performance, Orange = Average performance, Red = Worst performance

1.1.1 Li-ion Cathode Chemistries

Under the lithium-ion umbrella, there are multiple chemistries available in the market that are currently deployed in BESS installations. Their differences at the materials level are reflected in their differences in terms of performance, cycle life, cost, and sustainability. Among them, the three most popular Li-ion chemistries to date are:

- Lithium Nickel Manganese Cobalt Oxide (NMC);
- Lithium iron phosphate (LFP);
- Lithium Manganese Oxide (LMO)

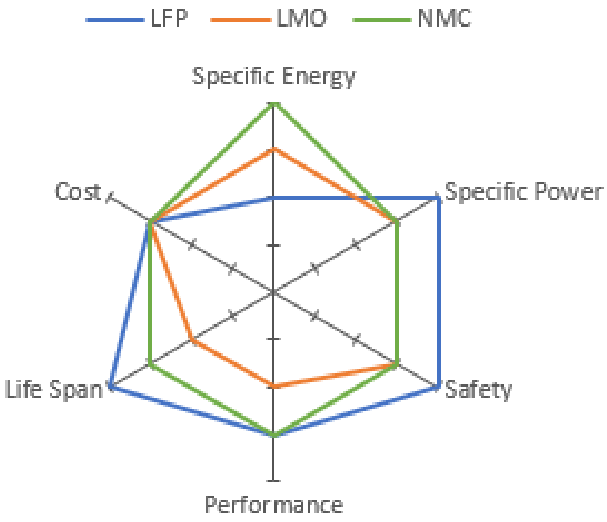
A comparison of their KPIs is reported in Table 3 and in Figure 1.

Table 3: Comparison of key performance indicators of different Li-ion chemistries[2,3]

Key performance indicators	NMC	LFP	LMO
Cell Nominal Voltage (V)	3.60, 3.70	3.20, 3.30	3.70
Cell operating voltage range (V)	3.00 to 4.20	2.50 to 3.65	3.00 to 4.20
Specific Energy (Wh/kg)	150-220	90-120	100-150
Energy Density (Wh/L)	500	350	350
Charge (C-rate)	0.7C to 1C	1C typical	0.7C to 1C typical, 3C max
Discharge (C-rate)	1C, 2C on some cells	1C, 25C on some cells	1C, 10C possible
Cycle life (cycles)	<6,000	<12,000	<1,000

[2] (Battery University, 2021).
[3] (Flash Battery, 2022).

Figure 1: Performance map comparing Li-ion chemistries



Lithium Nickel Manganese Cobalt Oxide ('$LiNMnCoO_2$' or 'NMC')

NMC chemistry is one of the current leaders for stationary applications and especially in the electric vehicle sector due to its high energy density, power density and high voltage, as shown in Figure 1.

The energy density of NMC depends on the ratio combinations of NMC elements. The higher the percentage of Nickel content, the higher the energy density of the battery. Even though the price of Nickel is four times higher than Manganese and the price of Cobalt is twenty-four times higher than the price of Manganese, the costs of cells using higher nickel content are decreasing, providing a significant decrease in cost per Wh. Also, NMC chemistries have the property of using the same materials to achieve different performance characteristics, this effect is called core shell gradient.

NMC has historically been the chemistry of choice for energy storage solutions and is one of the most prominent chemistries within the electric vehicle (EV) industry. Demand within the energy storage industry grew beyond the available supply between 2018 and 2019, thus driving developers towards LFP.

Lithium Iron Phosphate ('$LiFePO_4$' or 'LFP')

One of the main characteristics of LFP batteries is its nanometre size range, which allows to have faster charging and discharging rates. It also has a very flat voltage-discharge curve, but relatively low specific energy, shown in Figure 1. It is the low specific energy capacity that is the main disadvantage of this cathode chemistry. Owing to its thermal stability, the LFP cell has a major advantage: it passes all stress tests (nail penetration, crush tests, short circuit and any other mechanical test or tolerance on abuse) without thermal runaway. If safety is the main concern, LFP is generally considered the lowest-risk choice.

LFP is dominating the Li-ion battery chemistry market and will continue by 2028 and by 2030 demand for the chemistry will exceed 3000 GWh[4]. LFP is currently used for stationary battery solutions however, the technology is beginning to appear in EVs as a safer and cheaper option to NMC because of better performance in terms of cycle life. In addition, the materials used in the chemistry are more abundant and sustainable than in the NMC typology.

Lithium Manganese Oxide ('LiMn2O4' or 'LMO')

LMO has good electrical and ionic conductivity as it is insoluble in aqueous solutions. LMO cells have a high specific energy, shown in Figure 1, making it desirable in electric powertrains, electric vehicles and electric bikes, and it also has a medium cost. The main disadvantages of this technology relative to alternatives include lower capacity, increasing in losses during storage and cycling, and poor performance under high temperatures.

1.1.2 Lead Acid

Lead acid technology is very mature, with a mid-range power and energy density. The adequate specifications and the low cost of the older, more mature forms of lead acid batteries has led to lead acid batteries seeing widespread use in automobiles. Older forms of lead acid technology suffer from hydrogen and oxygen outgassing, which has resulted in safety incidents and limits their lifetime, and sulphation – the build-up of lead sulphate crystals on electrodes - which limits battery capacity. There have been several advancements in lead acid technology, most notably:

- Valve-regulated lead acid batteries – limits outgassing, thus increasing battery lifetime;
- Advanced lead acid batteries – the electrodes have carbon layers embedded onto them which prevents sulphation, leads to cost increases but these are alongside significant cycle life increases;
- Lead crystal batteries – uses a solidified electrolyte, so there is minimised leakage risk, presently only used in small-scale off-grid/residential applications.

The continual development of lead acid batteries and lead acid's established market-share for automotive applications are noteworthy (while utility-scale configuration is still rare). We consider, though, that the cycle life is lower than that of other electro-chemical technologies, which may result in higher costs over the lifetime of a project. A further downside of using advanced lead acid batteries is that lead is environmental concerns around toxicity, however, we expect the lead to be sufficiently contained within the battery casing. Lead acid batteries have established recycling means with typically over 95% of the battery can potentially be recyclable.

[4] (Energy Storage News, 2022).

1.1.3 Redox Flow

Instead of having electrodes fixed in the electrolyte like Li-ion, a redox flow battery (RFB) stores its electrolyte in separate tanks. The dominant type of redox flow technology is vanadium redox flow in which the electrolyte solutions are made of vanadium-ion compounds.

RFBs potentially have a lower cost per kWh on a Levelized Cost of Energy Storage (LCOES) basis compared to other electro-chemical technologies given the following advantages. Degradation is linked to rates of cross-contamination between electrolytes and thus replacement can extend useful life. Power and energy capacity capabilities are a function of ion-exchange surface area and the volume of electrolyte storage respectively. Additionally, depending on electrolyte chemistry and storage volumes these systems can release energy for longer time periods compared to other commercially available batteries. Naturally, these operational advantages come with increased OPEX costs.

A downside of this technology is the low energy and power density, limiting their application, and their complex architecture, which can lead to higher maintenance requirements than other technologies but potentially mitigated by a higher lifetime. The electrolyte is also classified as toxic. As a precaution to prevent any contamination of the surrounding environment, the electrolyte is contained within a closed system with a secondary containment to prevent electrolyte leaks. Although the electrolyte can be toxic, the aqueous phase allows for easier recycling.

Still, the scalability given by the ability to increase the energy capacity by only increasing the volume of the electrolyte tanks, and the long cycle and calendar life are attractive. Recent advances in vanadium flow batteries appear to show improved specific power and energy density, as well as the round-trip efficiency shows that redox flow batteries could be more competitive than Li-ion for utility scale applications within the next decade.

1.1.4 Upcoming batteries

Lithium Sulphur

Lithium sulphur (Li-S) uses sulphur as the electrode and metallic lithium as the anode. The theoretical energy density of this chemistry is four times greater than standard Li-ion. Saft claims many of the major technical barriers have already been overcome and the technology can be expected to reach market not long after solid-state li-ion.

Solid State Batteries

In solid state batteries, the liquid electrolyte in standard Li-ion chemistries is replaced by a solid compound. This technology is not new however, recent research has allowed previous technical barriers to be overcome. Key advantages of a solid-state battery is that it is non-flammable when heated and has a higher energy density compared to a Li-ion battery. A graphite based solid state battery is expected to be the first to market.

Sodium-ion

Research in Sodium-ion (Na-ion) batteries has revealed they could be a lower cost, safer, more environmentally friendly alternative to Li-ion chemistries. The technology is still in early development however, strong performance and improvements in density and cycle rates are promising and according to Wood Mackenzie, the technology could reach 20 GW by 2030 with the right investment.

A key benefit of Na-ion is the availability of sodium. It is not a finite resource and costs of extraction on purification are significantly lower than lithium. Quotes for Na-ion cells could be 20% to 40% cheaper than Li-ion with the key barrier currently being the scale of the technology. In addition, the increasing cost of lithium is making Na-ion more and more attractive.

CATL revealed their first-generation Na-ion battery in July 2021. They are expecting mass production to be achieved by 2023. CATL are reporting that their Na-ion batteries are achieving energy density values of up to 160 Wh/kg with the aim to exceed 200 Wh/kg.

Zinc Manganese Oxide

Zinc Manganese Oxide is a promising battery chemistry for use in grid-scale energy storage. The chemistry has shown a high theoretical energy density of ~400 Wh/L, in line with commercial Li-ion chemistries[5]. The batteries are thought to be safer than Li-ion and the components inexpensive and more environmentally friendly. There are however, challenges to overcome with the chemical and physical processes at the electrodes that are proving to be barriers in achieving competitive cycle life and energy density.

1.2 Short vs Long Duration

Duration of a BESS is defined as the length of time the storage system can discharge at its rated power before its rated energy capacity is depleted. For the purpose of this research, short term BESS duration refers to systems between 0.5- and 4-hour duration and long-term BESS duration refers to systems between 3- and 12-hour duration.

1.2.1 Short Duration

Short-term ancillary services generally solve issues related to imbalances within the electricity grid. BESS can provide the flexible, instantaneous response to rectify these issues. Li-ion chemistries are typically used for this role due to their fast reaction times and high energy density. Li-ion systems are typically designed between 0.5- and 4-hour durations.[6]

Ancillary services short duration BESS can provide include the following:

- Voltage support
- Frequency regulation and reserve services

[5] (Lim, et al., 2020).

[6] For durations beyond 1 hour, usually BESS provide peaking generation supply.

- Black start
- Peak shaving

1.2.2 Long Duration

When it comes to long term ancillary services for electricity grids, Li-ion batteries have certain limitations that make them less suitable for long-duration applications compared to other technologies. To be more precise, the cost of Li-ion batteries is directly proportional to their capacity, whereas flow batteries have a cost that increases at a slower rate with increasing capacity. This is because certain components of flow batteries, such as cells and electrolytes, are determined by power requirements rather than energy requirements, allowing for more flexibility in sizing the energy storage tanks. Consequently, flow batteries can offer a lower overall cost per kilowatt-hour of stored energy compared to Li-ion batteries, in which the cost is more closely tied to the total battery capacity. Given that flow batteries typically offer durations ranging from 3 to 12 hours, and have the advantage of unlimited potential energy capacity, they are more suitable for long-duration systems (despite requiring more physical space per kilowatt-hour of energy storage). Having said that, some long-duration Li-ion systems, with durations of up to 8 hours, have been deployed globally due to advancements in large-scale manufacturing and cost reduction for Li-ion technology.

Ancillary services long duration BESS can provide include the following:

- Firming capacity
- Congestion relief
- Power smoothing

1.3 Safety

Chemical batteries have a number of safety issues which need to be carefully managed. While uncommon, when batteries are operated outside of their recommended conditions failures can occur, which can result in severe consequences due to the high amount of energy stored in confined spaces.

1.3.1 Failure Modes

Failure modes describe the typical mechanisms that result in failure of a BESS. These are defined as the following:

- Mechanical Abuse - When a battery is physically damaged. For example, after being dropped, crushed or penetrated
- Thermal Abuse - When a battery is subjected to external heat sources
- Electrical Abuse - Can occur when the battery is overcharged, charged or discharged too rapidly or charged at a high voltage.
- Environmental Impacts - Seismic activity, rodent damage to wiring, extreme heat, floods

1.3.2 Failure Risks

Thermal Runaway

If large quantities of chemical and electrical energy are released, a thermal runaway can occur. This is when a battery cell rapidly releases more heat energy than it can dissipate safely. A thermal runaway can spread to neighbouring cells and may result in a battery fire or explosion. Li-ion batteries are the most susceptible to this risk however, valve regulated lead-acid batteries have been known to experience thermal runaway.

Stranded Energy

If a fire has occurred within a battery unit, there is often still energy stored. Discharge of this energy can be difficult if the terminals are damaged. This remaining energy has the potential to injure anyone performing overhaul after a fire or even reignite the fire up to a few days later.

Toxic and Flammable Gases

During thermal runaway, most batteries will create toxic and flammable gases. Toxic gases include Hydrogen Fluoride (HF), Hydrogen Cyanide (HCN) and Phosphoryl Fluoride (POF_3). HF forms Hydrofluoric Acid when in contact with water. HF is toxic or lethal if inhaled, ingested or comes into contact with skin. If large quantities of these gases are released during a battery fire, surrounding populations may be at risk.

Flammable gases including Hydrogen (H_2) Carbon Monoxide (CO), Methane (CH_4) and Ethylene (C_2H_4) can be formed during a thermal runaway. If the gases do not ignite, they can build up inside the BESS container and create an explosive atmosphere.

Deep Seated Fires

BESS consisting of many battery cells are typically housed in metal or plastic casings in large containers. These protective casings help to prevent damage but in the case of a fire can prevent water from reaching the origin of the fire. As a result, a large amount of water is required to dissipate the heat.

Electrolyte Spill

The electrolytes contained within RFBs and lead acid batteries can be harmful to humans and the environment. If in contact with skin, burns may occur. Suspected contact should be rinsed under water and as a precaution protective clothing, safety glasses, mask and gloves should always be worn when dealing with an electrolyte spill.

To prevent harm to the environment after an electrolyte spill, the spill should be contained with sand or earth and the contaminated material removed and safely disposed of after it has completely soaked up the electrolyte. The area should then be washed to neutralise any residual acid.

1.3.3 Mitigation and prevention

Fire Suppression System

Normally inert gases are used first and water is seen as a last resource when trying to cool a battery fire. Additionally, sprinkler systems could be installed alongside batteries.

Battery Management System

A Battery Management System (BMS) monitors, controls, and optimises performance of batteries and can disconnect a module from the system if it detects abnormal conditions, such as overcharge, or overtemperature. It ensures that the system operates within design parameters.

Spacing

Battery units should be segmented into certain sized kW / MW units and spaced appropriately to reduce the likelihood of horizontal propagation.

1.4 Battery Degradation

Degradation of a battery can be considered either physical or chemical. Identifying battery degradation mechanisms is difficult during operation but the effects of the degradation can be identified with drops in capacity or power (even though unlikely).

1.4.1 Li-ion

Degradation is natural in Li-ion batteries however, extreme usage patterns and operating conditions can increase the rate of degradation. There are three key external factors that influence Li-ion degradation: temperature, state of charge (SoC) and load profile. The specific chemistry of the battery dictates the scale of impact of each of the factors, however, temperature is the most significant factor. Temperatures deviating from the optimal temperature (25°C) will increase the rate of degradation and the chance of complete failure.

Li-ion degradation can be described by the chemical and physical changes that the cell undergoes, the observable effects that indicate degradation has occurred and the mode of degradation which is used to group degradation mechanisms based on their impact on the thermodynamic and kinetic behaviour of the cell. Mechanisms of Li-ion battery degradation that reduce cell capacity include irreversible chemical side reactions such as:

- Solid electrolyte interphase layer growth
- Lithium plating

There are some mitigation methods that can reduce the rate of degradation.

- Avoiding prolonged periods at full charge and high temperatures.
- Charging and discharging at a slower rate
- Well-managed partial depth of discharge

- Carefully designed BMS to monitor the State of Health (SoH) and disconnect the battery if there are abnormalities.

1.4.2 Lead Acid

A 'shelf-life of a lead acid battery is 5 years. In reality however, consistent use of the battery will accelerate degradation. Methods of degradation can include:

- Deformed plates from deep cycling of the battery resulting in reduced charging ability or electrical shorting.
- Acid stratification as a result of not storing the battery in a fully charged state, reducing charging ability.
- Sulphate crystallisation on the plates in inevitable however, the rate at which the deposits form is increased by:
- Increased temperature, accelerating self-discharge
- Not fully charging the batteries and leaving the in mid-charged states for long periods of time
- Over charging

1.4.3 Redox Flow

There are a number of processes that can occur in a vanadium redox battery that reduce its performance, mostly due to imperfections in the membrane. These include:

- Direct permeation of vanadium electrolyte across the membrane resulting in an imbalance in electrolyte concentration
- Gas evolute side reactions. Hydrogen is the most common gas produced which competes with the vanadium redox reaction
- Vanadium precipitation occurs when there is an imbalance in electrolyte concentrations and results in damage to the membrane.

Electrolyte crossover can be resolved and balance across the electrolyte tanks can be restored by simply remixing the electrolytes across the reservoir tanks. For Gas evolute and Vanadium precipitation, a more complex electrochemical method is required. Any damage to the membrane or electrodes is fixed by simply replacing the affected parts.

1.5 Plant components

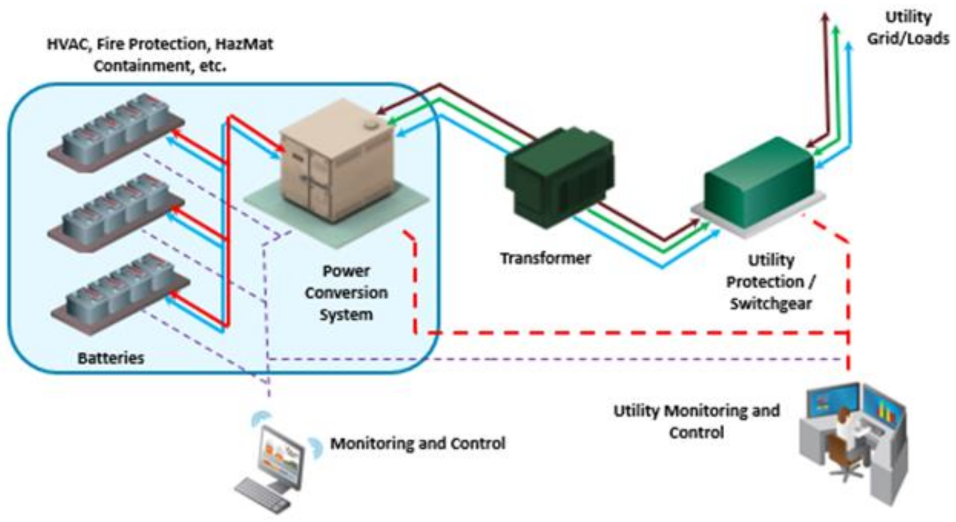
The most important plant components include (see Figure 2):

- BESS Containers
    - Battery modules
    - Heating, Ventilation and Air Conditioning (HVAC)
    - Fire suppression system
- Battery Management System
- Power Conversion System (PCS) (inverters and low to medium transformers)
- Switchgear

- Supervisory Control and Data Acquisition (SCADA)
- Civil works
- Grid connection

A more detailed description of each component is described in the following sections and an overview of the costs associated with each of the components is presented in Section 1.5 of Part 1.

Figure 2: Components of a BESS[7]



1.5.1 BESS Containers

Modules

Li-ion battery modules are enclosures which combine groups of cells into larger modular units. The modules are then stored in racks that ensure the modules are adequately spaced to allow for thermal contraction and expansion and allow adequate spacing for cooling. The racks are stored within containers that provide protection from the climate and weather and house additional components such as the BMS, the HVAC, and fire protection.

Vanadium Redox batteries are composed of two tanks that contain positively and negatively charged electrolytes. The two electrolyte solutions are pumped through a cell stack where the electrolytes are separated by a thin membrane to prevent mixing. Ions are able to pass across the membrane during charge and discharge of the battery. Multiple cell stacks and larger electrolyte tanks increase the capacity of the battery. Lead Acid batteries consist of a negative electrode and a positive electrode submersed in an electrolytic solution. Similar to Li-ion, the lead acid battery modules can then be stacked within a container.

[7] (EPRI, 2021).

HVAC

The HVAC system provides internal thermal regulation for the BESS in order to maintain requirements and stability of the batteries and other housed equipment. The climate control system should be designed to be able to maintain the internal environment, as it operates within the expected extremes of ambient temperatures. The system should first be sized for the highest intensity service profile, including all heat loads of the system and external environmental conditions, and subsequently oversized to account for a single component failure of the climate control system:

- The HVAC system should incorporate a redundant design, where by one single fault should not result in the loss of a complete system in a container/enclosure. The system would instead be allowed to de-rate in the event of a fault.
- The system should be sized with sufficient capacity to thermally regulate the container/enclosure and provide the correct level of circulation around equipment, in the event of additional capacity being added to containers up to full potential augmentation/redistribution capacity such that it is not expected that retroactive works are required to the HVAC system, unless there is a commercially applicable reason for this design choice.

The HVAC system should be designed for the physical dimensions, climatic variance and noise restriction requirements to minimize the electrical demand, and the associated long-term OPEX and potential REPEX of the HVAC system.

Fire Suppression

Depending on the specific voltage, temperature, and operational ranges, failures can occur, and fire safety systems play a very important role for detection and suppression. Battery failures most commonly lead to combustion. As a result, BESS and associated facilities should be designed and built with provision of a safe operating environment for equipment and personnel with the properties of Li-ion in mind. Where applicable, this should be achieved by separation and segregation of equipment with sufficient distances and materials, as well as appropriate levels of contingency and a design which accommodates expected failure modes. Additionally, the fire suppression system should:

- Be provided for the core energy storage equipment such as the battery containers/enclosures and should be designed, supplied and installed in accordance with local and national certification and legislative requirements to comply with the local fire safety law.
- Have its own back-up power supply system to maintain protection in the event of a loss of primary power to the fire suppression system and should self-diagnose and report the presence and general location of faults to the monitoring system.

1.5.2 Battery Management System

The BMS is required to manage each individual battery. The BMS measures voltage and temperature to provide data on the health of the battery in order to improve its performance and longevity and, ensure the safe operation of the battery. The BMS communicates with the Energy Management System (EMS) to ensure the BESS system as a whole is functioning efficiently and safely.

1.5.3 Power Conversion System

The PCS is a critical part of a battery project as it controls the power flow between the battery and the grid. A PCS serves two key purposes:

- Connecting otherwise incompatible forms of electricity. For example, AC and DC sources, DC sources with differing voltages, AC sources with differing frequencies
- Control over the flow of electrical energy in a system.

The number of PCS cabinets required is determined by the nominal power capacity. In addition, the DC voltage range of the PCS must be large enough to cope with the maximum and minimum voltage of the BESS. Depending on the project size and integrator design choices, PCS can either be integrated within the containerised BESS solution or separated in its own enclosure. The benefit of an integrated PCS is its compactness and the reduction of LV DC cabling which reduces the costs and Electromagnetic Compatibility (EMC) emissions. On the other hand, maintenance can be more complex compared to a split battery/PCS configuration. Installation of PCS on site is drastically simplified when integrated as it will be most likely installed and configured to the application requirement at the factory. Currently, BESS are typically designed to be ‘grid following’ where the inverter follows the frequency of the grid. PCS’ used in grid following systems cannot offer services such as black start and synthetic inertia. As a result, an increasing number of ‘grid forming’ PCS’ for BESS are being developed. Grid forming BESS have the ability to set the frequency of the grid and replace the role typically performed by thermal generators.

1.5.4 Transformers

Transformers are necessary pieces of equipment to interface a battery to the grid. The main objective of the transformer is to perform a voltage adaptation for the LV output of the PCS to the grid voltage. It also provides galvanic insulation which is critical for the earthing design. Depending on the grid voltage, several transformers might need to be cascaded to be cost effective and to provide redundancies.

1.5.5 Switchgear

Battery projects connected to the grid at the Medium Voltage and upward will require a switchgear. The reliability of the electrical grid is directly dependent on the switchgear, which basically consists of switches, fuses and circuit breakers used to manage electrical equipment. The switchgears are generally installed in a separate building/container with all control and communication systems (SCADA).

1.5.6 Control and Monitoring System

A monitoring and control system such as the SCADA system allows the BESS to be self-sufficient in controlling its performance and ensuring efficient operation. A number of sensors feed information to the control system and allow for the monitoring of factors including internal temperature, energy usage and identification of any module failures.

1.6 Leading Battery Suppliers and BESS Integrators

In this section, the main players involved in BESS integration are reviewed. Battery suppliers (or Original Equipment Manufacturers, OEMs) manufacture battery cells and BESS integrators (or vendors) offer the BESS supply and potentially the EPC services required to implement BESS projects. For each BESS supplier assessed in this section, a general review of key entity characteristics is provided.

1.6.1 Battery Suppliers

The manufacturing process of energy storage cells is a highly sophisticated and automated process that requires considerable investment. As such, only large companies are able to supply batteries of sufficiently high quality needed for a large-scale BESS. The following OEMs are considered the main players in the field:

- CATL
- BYD
- LG Chem
- Samsung
- Panasonic
- Tesla

1.6.2 BESS Integrators

In this section the key BESS integrators are presented and are summarized in Table 4, ranked based on current market capitalization. Market capitalization (market cap) represents the total value of a company's shares of stock. The group revenue describes the total income generated by the entity through sale of services or products to consumers.

Table 4: Key BESS integrators

Company	Country	Current market cap (USD billion)	Group revenue / year (USD billion in 2021)
Tesla	USA	762	54
BYD	China	114	32
NextEra Energy	USA	147	17
LG Energy Solution	Korea	90	15
Nidec	Japan	37	15
Sungrow	China	17	14
Samsung SDI	Korea	30	12
Doosan Enerbility	Korea	10	10
Wärtsilä	Finland	5	6
Canadian Solar	Canada	2	5
RES-Group	USA	3	3
Aggreko	UK	3	1.4 (2020)
Fluence Energy	USA	0.5	0.7
Akuo	France	NA	0.3 (2020)
Powin Energy Corporation	USA	0.3	0.05 (est.)

1.7 Global BESS Capacity

At the end of 2021, IEA reported 16 GW of installed grid-scale battery storage capacity, 6 GW of which was installed in 2021 with the United States, China and Europe contributing the largest shares. An additional 11 GW of capacity was added in 2022, a 75% increase from 2021.[8]

The IEA 2050 NZE Scenario suggests global energy storage installations need to increase to 590 GW by 2030 and to 3,100 GW by 2050 to ensure the target of net zero CO_2 can be met. This will require annual deployment of batteries will need to increase to 120 GW in 2030 and more that 240 GW in 2040[9]. The scale of the increase in capacity required can be visualised in Figure 3.

BloombergNEF[10] predicts that global cumulative energy storage will reach 411 GW / 1194 GWh by the end of 2030, 15 times the capacity currently recorded. The divide between specific countries and regions is shown in Figure 4. This projection falls short of the Net Zero Scenario requirement which only covers grid-scale storage not accounting for storage in homes and business which BNEF forecasts to account for one quarter of global storage installations by 2030.

[8] (BloombergNEF, 2023).
[9] (IEA, 2021, pp. 117-118).
[10] (BloombergNEF, 2022).

Figure 3: Energy Storage Installations Predictions (GW installed)

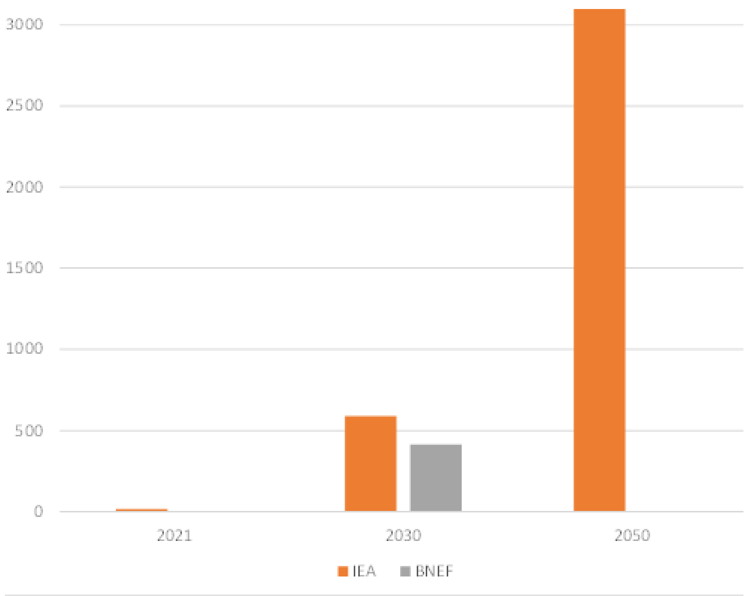
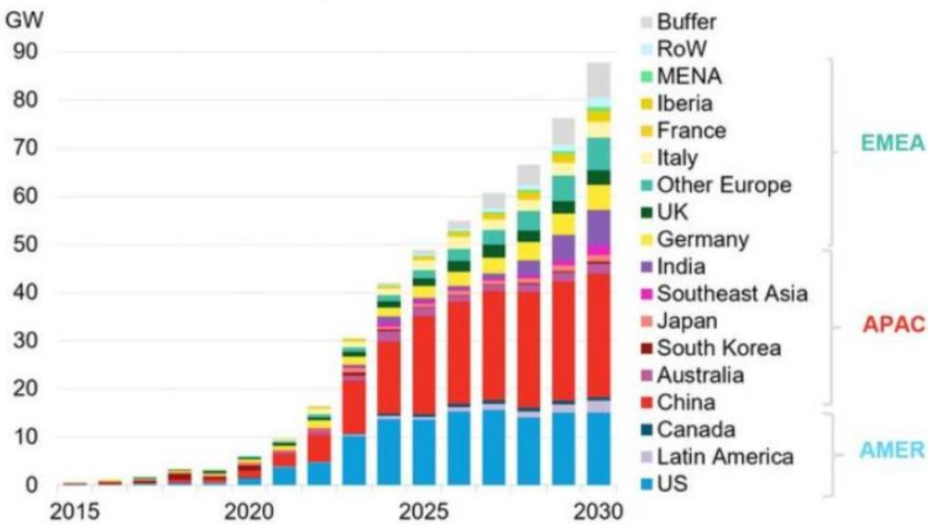


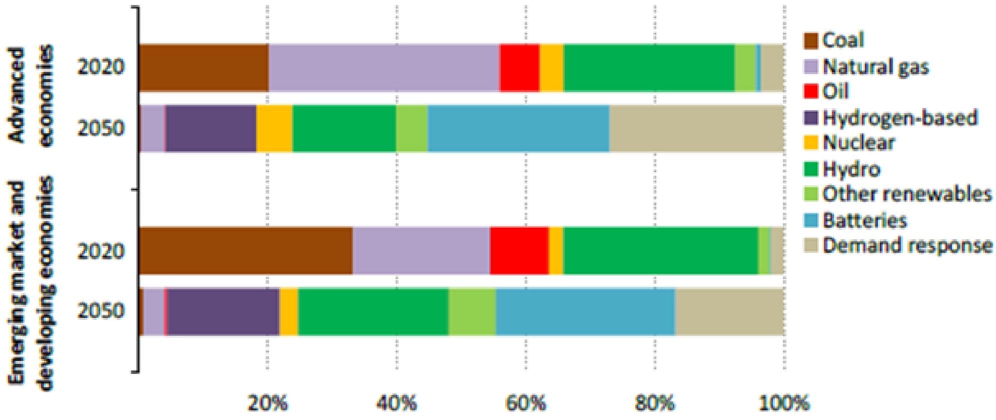
Figure 4: Global gross energy storage installations, 2015 - 2030[11]



As variable renewable energy generation is increased and gas and oil-fired power plants are retired, batteries will be critical in ensuring energy security. Batteries will provide flexibility to the electricity system as shown in Figure 5, alongside demand response and hydro solutions.

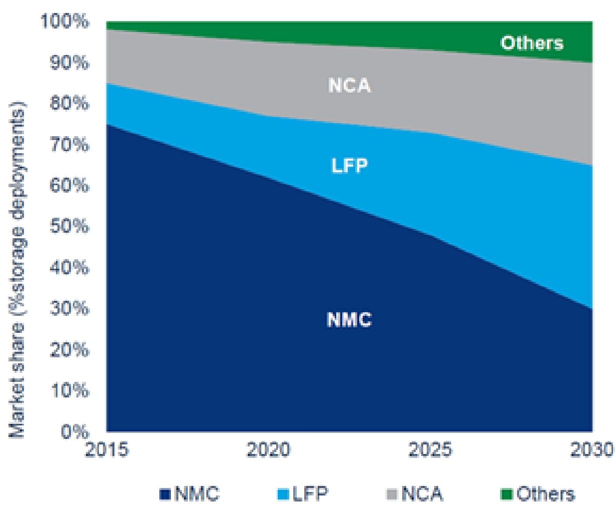
[11] (BloombergNEF, 2023).

Figure 5: Electricity system flexibility by source in the NZE[12]



IEA expects the battery deployment market to be dominated by India, the United States and China by 2040.[13] Figure 6 shows the split between Li-ion chemistries from 2015 until 2030. The market share of NMC has been continuously decreasing with LFP and other chemistries taking up a higher percentage of the share. Worth noting that relative proportions only, while the overall cumulative deployment of batteries is expected to grow, as mentioned above.

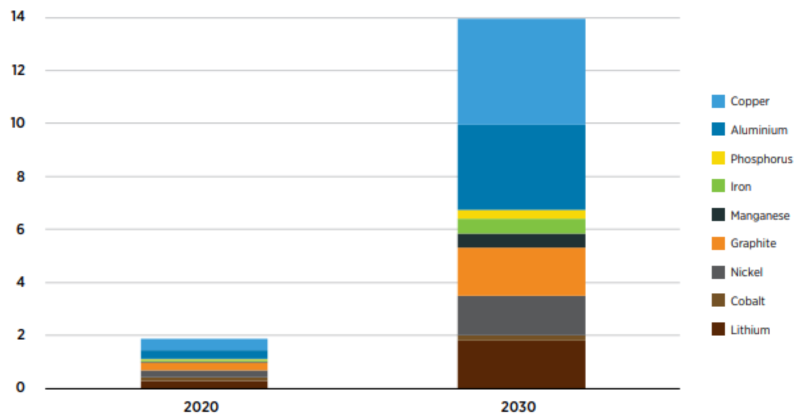
Figure 6: Energy storage market share until 2030[14]



[12] (IEA, 2021, p. 177).
[13] (IEA, 2021).
[14] (Wood Mackenzie, 2020).

As demand for BESS installation increases, so too will the demand for the materials required to construct them. Figure 7 shows the projected increase in BESS raw materials from 2020 to 2030. An increase of 7 times overall with copper and aluminium being in the highest demand. The cost of materials critical to batteries will be a factor in dictating the future installed capacity of battery chemistries.

Figure 7: Projections for demand for battery materials (million metric tons)[15]



[15] (IRENA, 2021).

2 BESS Grid Services

BESS deployment for stationary application can be divided in two types of market applications: front-of-meter (FTM) and behind-the-meter (BTM) applications. FTM is usually referred as a grid-scale or utility scale battery storage with capacities ranging from a few MWh to the order of 1 GWh.[16] This type of application can be interconnected to distribution/transmission lines or power generation assets and provide services to network operators such as ancillary services, network load relief and peak generation (see Table 5). Lithium Ion is the most prevalent battery technology used for FTM deployment ensuring high reliability, high performance, and high efficiencies. Almost all utility scale generation facilities feed into the grid network with energy produced via fossil fuels and renewable energy e.g., wind, solar and geothermal. The battery storage facilities designed for FTM application are connected directly to transmission or distribution grids and are not behind a customer meter.

BTM application is referred to as small scale battery storage which can be used in micro-grid, mini-grid settings and usually connected through electricity meters for commercial, industrial and residential customers. The size of the BESS can range from 3 kW to 5 MW, and it is typically paired with solar PV. BTM batteries are typically placed on the customer side facility reducing the distribution system operators (DSO) direct control of the system. There are, however, some initiatives in place that allow DSOs to withdraw electricity when needed.

The initial deployment of BTM BESSs showed its ability to provide back-up power to consumers during stages of black-out and provide frequency and voltage support for the grid. Using BTM has allowed for a significant improvement in the resilience of power supply, reducing peak load in the grid systems and cutting electricity bills for many of its consumers using the time-of-use tariff scheme. Although, the market is currently dominated by utility-scale batteries (FTM), small scale batteries such as BTM is expected to increase. In 2017, IRENA shows BTMs providing energy services of less than 25 GWh which by 2030 is projected to increase over 100 GWh.[17]

Table 5 highlights all the services provided by BESS FTM and BTM. Services for FTM which could be useful for BESS in Tunisia are split into four categories: generation, transmission, ancillary and distribution.

Table 5: Services provided by FTM and BTM BESS[18]

Front-of-Meter	Behind-the-Meter
Generation/ Bulk Services: • Arbitrage • Electric supply capacity	• Peak shaving and demand charge management • Time-of-Use energy cost management

[16] (Connected Energy, n.d.).
[17] (IRENA, 2019).
[18] (Sifat Amib, 2020).

Front-of-Meter	Behind-the-Meter
• Support to conventional generation • Ancillary services RES support • Capacity firming • Curtailment minimization • Limitation of upstream disturbances	• Continuity of energy supply during the outage of electricity supply utility • Power quality management and limitation of upstream disturbances • Reactive power compensation • EV fast charging
Ancillary Services: • Frequency Control • Frequency stability of weak grids • Voltage support • Black Start	
Transmission Infrastructure Services: • Transmission investment deferral • Angular stability • Transmission Support	
Distribution Infrastructure Services: • Capacity support • Contingency grid support • Distribution investment deferral • Reactive power compensation • Dynamic, local voltage control • Intentional islanding • Limitation of upstream disturbances • Distribution power quality	

Lithium -ion is one of the most common battery technologies currently deployed in BESS along with other battery technologies such as Lead Acid and Vanadium Redox Flow. All services are provided by these battery technologies with varying performance capabilities depending on their usage e.g., frequency regulation, arbitrage. Lithium -ion and Lead Acid have high performance indicators that allow for these technologies to be used in both commercial and industrial purposes.

2.1 BESS Grid connection

BESS systems can be connected to the grid in two different ways: stand-alone or co-located. The standalone application is when the BESS is directly connected to a node of the grid, and not necessarily in the vicinity of a renewable energy source (RES). The main aim of this type of application is to provide grid services to improve the stability and quality of the power network. In a co-located project, the BESS is installed in close proximity to an intermittent RES (such as solar farm or wind farm) or with a deeper integration where, for example, the two have a single connection point to the grid. The two assets are connected to promote the interaction between them and to allow some of the BoP components to be shared between the two. Operating strategies of the two assets are often linked together and focused on optimizing the use of the energy generated by the RES, for example by promoting clipping recapture, curtailment recapture, and time shift. Co-located plants can be subdivided into two macro-categories, depending on the position of the BESS connection: AC-coupled or DC-coupled. Section 2.2 of Part 1 describes these connections in further detail, highlighting the advantages and disadvantages of each application.

2.1.1 Standalone

Figure 8 shows the configuration of a stand-alone project where both battery and RES technology (Solar PV as an example) exist separately. Each has its own inverter and grid connection. A stand-alone BESS solution can be designed to suit any storage duration requirement. In all cases, standalone BESS are charged using energy from the grid, ideally during off-peak periods. The power from the batteries is then discharged either when the grid is not able to distribute power due to power outages and cuts or during peak demand periods to aid with load shifting.

Some of the major benefits of using a stand-alone containerised solutions are the ability to increase the scale of the unit. By adding more battery containers, the capacity of the service increases. Some of the lithium-ion batteries used in this type of application are designed to last from 2 hour to 8 hours. Utilities that use stand-alone BESS solutions are also able to see a reduced emergency peak generation. As demand starts to increase on the grid, extra transmission lines are required to support to additional demand for energy. A BESS system deployed at a sub-station or on a loaded line can relieve this congestion. BESS is able to inject the correct amount of stored energy during peak consumptions to alleviate pressure on transmission lines, reducing the need to upgrade transmission lines, reducing transmission losses, stabilising end user voltage and eliminating any power quality issues. During the low consumption periods, the batteries are able to recharge.[19]

2.1.2 Co-located

Co-located BESS projects (see Figure 8) have the same connection to the grid than standalone projects. The application can either be AC or DC coupled, depending on which point is the BESS connected with the RES. The most common type of co-located projects involves AC coupling. In this application batteries and solar PV are connected to separate inverters before sharing the same grid connection. Co-location can also be connected via a DC connection, where the battery system and solar PV panels are connected to the same DC bus ahead of the inverter.

One of the downsides of the AC coupling is the constraints on the export capability of the system. Figure 8 shows an AC coupled connection where the solar PV and BESS is generating and exporting energy through a single connection. In order to respect grid capacities and not cause cut-offs to the export capacity, both Solar PV and battery are unable to export energy at full power at the same time. This is a limitation of AC and DC coupled.

[19] (Bushveld Energy, 2020).

A solution is to alter the battery operating system around this constraint. When Solar PV is not generating around the night-time period, the grid connection has a power headroom allowing BESS to export energy at full power. During the day-time period, the solar PV system is able to perform at maximum capacity whilst the battery system normally can be used to stabilize the production of electricity. In this instance, BESS can increase the combined project profitability by shifting production from hours of low demand to peak hours, but it is also useful for ancillary services for TSOs and DSOs.[20]

Figure 8: Stand-alone, AC-coupled and DC-coupled configurations20

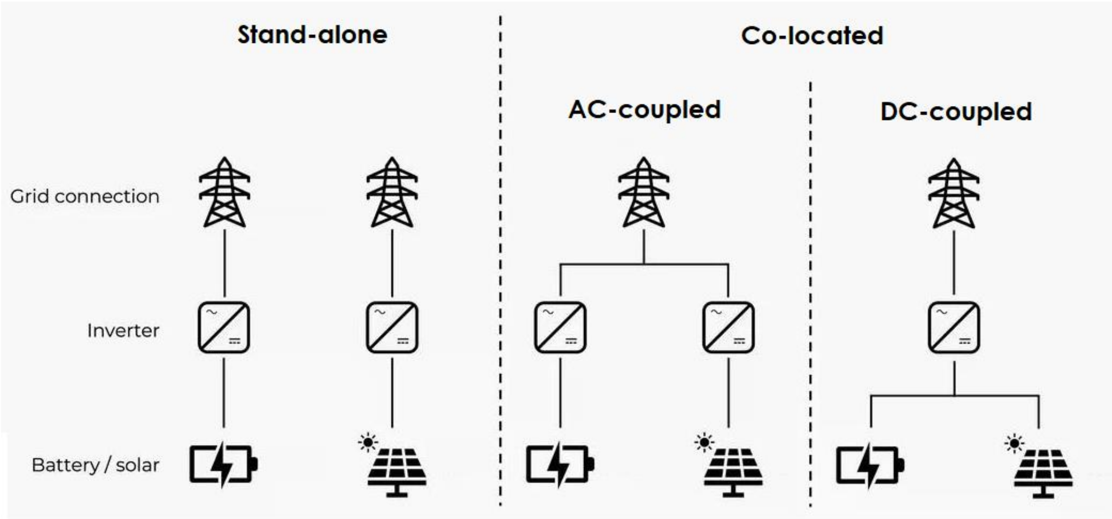


Table 6: Grid Connection Advantages

Characteristics	Stand-alone	Co-located (AC-coupled)	Co-located (DC-coupled)
Flexibility of Services	Higher	Medium	Lower
Overall conversion efficiency	Lower	Medium	Higher
Cost of infrastructure and implementation	Higher	Medium	Lower

2.2 AC-coupled and DC-coupled

Battery installations can be connected to renewable generation in two ways: AC or DC coupling. This type of connection falls under the sub-categories of co-located BESS plants.

[20] (Hortop, 2022).

2.2.1 AC-coupled BESS

AC-coupled BESS is connected in AC (typically MV) with a renewable generator and sharing a single connection point to the transmission or distribution grid. In an AC-coupled system, any electricity stored in a battery system will need to be converted twice if it comes directly from grid, three times if it comes from the PV. The DC electricity will flow into an inverter that transforms the DC to AC for export. If, however, energy needs to be stored in the batteries, the DC power is transferred to batteries. When electricity is required, the DC stored energy is then converted to AC via a power unit.

Some of the advantages of using an AC coupled system include retrofitting where a RES plant is already installed and also allows for easier expansion if required. Battery technology used within the system is advanced, reliable and robust ensuring that any faults do not impact the entire connection. There is also flexibility in inverter placement within the system where inverters and batteries are not restricted to location and can be installed at cooler temperatures e.g. 20°C.[21] In other words, that the design, installation and maintenance are simpler and can be better optimized. One of the other advantages of AC coupled systems is the versatility of charging. If the system has a solar PV connection that is unable to generate electricity, the AC system has the option to draw energy from the grid.

2.2.2 DC-coupled BESS

In a DC coupled system the battery unit has a direct connection to PV solar panel and a hybrid inverter. Direct current (DC) is able to flow throughout the unit and will only need to be converted to AC when power is exported. In contrast to the AC coupling set-up, DC requires less hardware and is therefore more affordable due to the reduced costs. Additionally, with power being converted only once throughout the unit, DC coupling is 3% more economical and efficient. DC also provides the opportunity to increase power production by adding more PV panels with the same inverter connection. By oversizing the PV system, any excess energy can be re-directed to charge the batteries.

However, with a DC coupling connection, it is not always possible to import energy from the grid which can have an impact on cost. There is also less flexibility in connection for DC as the batteries are expected to be in close proximity of the inverter; this results in higher installation and maintenance costs for BESS that partially offset the saving (for this reason, normally, the AC coupling is not common in large scale projects). In AC connection, this is not an issue.

[21] (Deege Solar, 2022).

3 BESS Pricing

As BESS becomes a more integral part of our modernising grid system, its adoption has allowed for an improved grid network where electricity supply, generation, transmission and distribution are more reliable, robust and flexible. A rise in global demand for BESS, as well as the demand of the same components from the EV industry, in the last decade has also resulted in its cost to become more competitive in the energy market. Since 2010, BESS has seen significant drop in prices and one of the main factors of the decrease has been the exponential advancement in battery technology and BESS deployment globally.

Market research from 2021 by BloombergNEF predicts that battery market share prices for storage deployment will see a significant decrease in lithium-ion prices; LFP to fall by 15% and NMC to fall by 35% by 2030. However, it is important to note that the impact of COVID-19 has not yet been completely absorbed by the market.

BESS costs are generally split into two categories known as Capital Expenditure (CAPEX) and Operational Expenditure (OPEX). Section 3.2 discusses the detail of market cost projections for the next 30 years and the potential impact in the industry for innovative battery technologies.

The following data analysis by RINA on costings does not reflect the effect from the COVID-19 pandemic in the BESS market. All prices and projections presented can be used as an approximation guide to understand the costings of BESS in the current market. This is considered on all prices mentioned in Section 3.1.

During the pandemic industries suffered losses globally throughout the battery energy storage market. Lockdowns imposed by countries between 2020 – 2022 has severely impacted supply chains across the globe with declines in demand and smaller production resulting in raw material shortages. With industries operating again in 2022, the BESS market has seen a growth in demand for installations in operational projects and more focus from governments to modernise their power sectors.

3.1. CAPEX and OPEX

CAPEX and OPEX are two important aspects of BESS, highlighting specific financial areas of projects. CAPEX includes costs related to the plant, infrastructure, equipment, development and site costs as shown in Table 7. OPEX includes costs related to operations and maintenance (O&M) costs, general and administrative expenses, land lease, labour, general maintenance on plant infrastructure and equipment, development of a project and cost of goods as presented in Table 8.[22]

[22] (U.S. DOE, 2021).

A more detailed overview on BESS pricing covering aspects of CAPEX and OPEX is presented in the following subsection. These expenses are highly variable depending on project capacity and duration and RINA recommends that the prices are considered as a guide.

3.1.1 CAPEX ESTIMATION

A breakdown of the most typical item categories that are included under CAPEX costs is presented in Table 7: BESS CAPEX item Categories.

Table 7: BESS CAPEX item Categories

Expenses	Items
Battery system and battery integration	Battery rack Battery management System (BMS) Battery Housing production and integration (internal wiring and component installation HVAC system Anti-intrusion and Anti-rodent system Fire detection and suppression system DC panel, cables and accessories
Balance Of Plant (BOP)	Power conversion system (PCS) PCS housing Metering devices LV DC and AC wiring and breakers MV/LV power transformer MV switchgear MV field cables Auxiliary systems Ventilation system BESS control and SCADA system Civil works (foundations, cable ducts, fences, drainage system, etc.)
Interconnection	HV/MV substation HV line
Other Costs	Engineering Land Acquisition Authorizations Internal costs Contingencies

BESS costings published by market analysts such as BloombergNEF, which uses another but similar classification of CAPEX items, provides an 11-year forecast of a 20 MW/ 80 MWh project as representative use case, detailing the cost estimation of the components and services.

Figure 9 gives an example of cost breakdown for CAPEX. The trend shown in this graph provides a sensible forecast of BESS pricing declining in the near future. However, it is important to note that these predictions can be altered with impacts to supply chains and increase in raw material costs which have occurred in the second half of 2022. An example of this is a Chinese manufacturer having increased the cost of LFP batteries by 10%-20% due to lithium carbonate prices.

Figure 9: Cost breakdown and forecast for 2019-2030 for 20 MW/ 80 MWh

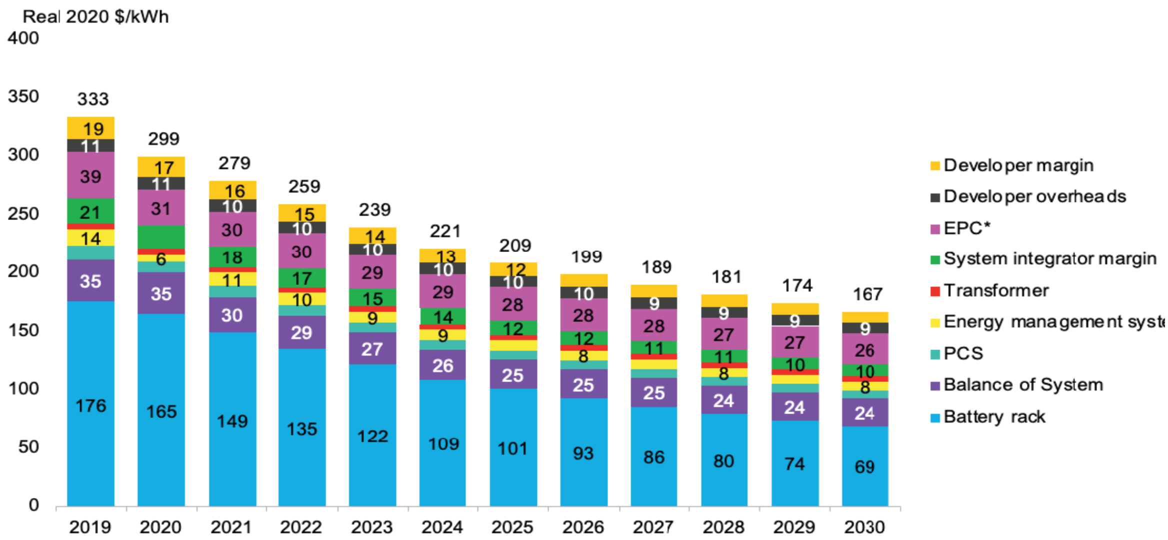
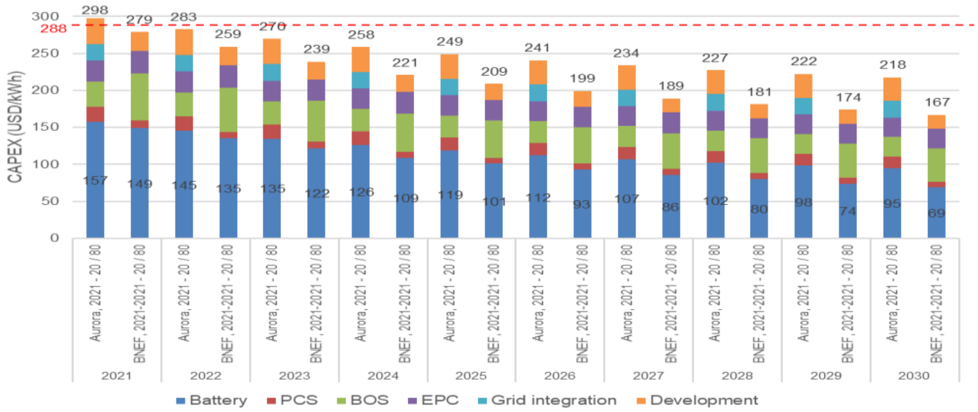


Figure 10 also provides data gathered from reputable market analyst sources such as BloombergNEF and Aurora that backs up the data for BESS cost declination in the future. The baseline estimation for 2021 is slightly different (298 $/kWh vs. 279 $/kWh), but this spread is increased during the following years. Each source considers its own cost reduction scenario, especially for the battery rack. While Aurora considers and average annual cost reduction of 3.4%, BloombergNEF gives a more optimistic perspective and increases it to an average 5.5%. In order to set a common criterion, if the baseline cost and its annual decline as an average of both references are modelled:

- Baseline 2021: 288 $/kWh
- Annual cost decline of 4.5%.

Figure 10: 2021-2030 cost forecast for 20 MW/ 80 MWh project



3.1.2 OPEX ESTIMATIONS

A breakdown of the most typical item categories that are included under OPEX costs is presented in Table 8.

Table 8: BESS OPEX Item Categories

Expenses	Items
Fixed Costs	administrative, labour, insurance, land lease, operating labour, property taxes, site security and taxes.
Maintenance Expenses	general, scheduled and unscheduled.
Variable cost	waste disposable and consumables.
Maintenance	Transformers, switches, grid/BESS equipment.
Replacement	This varies on project. Usually, batteries in ESS are warrantied with data on the duration of the cycle and lifetime.

RINA compiled general cost information from public reports and own experience. Typically, these costs are divided in the following categories:

- Fixed O&M costs: Those necessary to keep the BESS operational and do not depend on the energy throughput: planned maintenance, spare parts, permit fees, property taxes, insurance, operator/route-to-market contract fees, day-to-day operation workforce & labour costs, etc. This is the main part of OPEX for a BESS.
- Variable O&M costs: Usage impacted costs associated with non-energy consumables, safety & HVAC systems and disposals essential to operate the BESS. They are highly dependent on the application (duty-cycle / dispatch strategy) and the annual discharged energy. It can be considered close to zero if the capacity maintenance fees are excluded.

Table 9 shows general figures for fixed O&M costs, based on public data available on US Department of Energy Report.[23]

Table 9: Fixed annual O&M costs per technology and BESS size, USD/MW

	1 MW/ 4h	10 MW/ 4h	100 MW/ 4h
NMC	$ 4510	$4130	$ 3890
LFP	$ 4400	$ 4030	$ 3790

RINA highlights that BESS O&M costs can vary significantly depending on the level of service required. One of the most relevant parameters that can impact the O&M contract cost is the performance guarantees required by the buyer. It is also typical within the BESS industry for the EPC to perform O&M for the first 1 – 2 years following site completion, including that charge in the CAPEX price. Therefore, the values above should be taken carefully.

In order to give another sample of real costs, some figures based on experience are shown in Table 10. The information is based on UK based projects, covering preventive & corrective maintenance.

Table 10: Fixed annual O&M costs for Li-ion technology per BESS size, in USD/ MW

	50 MW /1h	50 MW / 2h	100 MW / 1h	100 MW / 2h
Li-ion	$ 4800	$ 6500	$ 3700	$ 5600

3.2 BESS Cost Estimates 2020 – 2050

BESS cost estimations by Aurora are presented in Figure 11, Figure 12 and Figure 13 below. These figures show a cost projection for 29 years for varying ranges of battery duration (0.5 hr, 1 hr and 2 hr, respectively). The graphs show that batteries with higher duration will result in higher BESS costs, but these costs are likely to decrease in the next few decades. The common trend between projections from Aurora and other market analysts highlights that BESS costs are likely to decrease in the coming years. If we factor in the COVID-19 impact on the market, the cost may not decrease to that extent projected in the figures, however, once the market is able to recover it is likely that BESS costs will fall. This is further supported in our report with suggestions of advanced battery technologies and the need to meet the new IRENA net-zero 2050 targets. Governments are also providing higher funding in renewable battery projects to increase the development of such technologies,[24] and therefore, increasing the opportunities of integration of remote locations.

As shown the figures below, a fall in CAPEX costs will also aid the BESS integration in developing countries such as Tunisia, where BESS in conjunction with RES e.g., Solar PV can see huge benefits for both the grid and consumer side. We can see that implementation of BESS continues to increase

[23] (U.S. DOE, 2013).

[24] (Partners, 2020).

with demand for production and materials on the rise. With more integration of BESS globally, it provides Tunisia with excellent opportunities to build larger standalone BESS plants to enhance its grid system operation.

Figure 11: BESS cost estimation 2021-2050 for 0.5 h battery systems

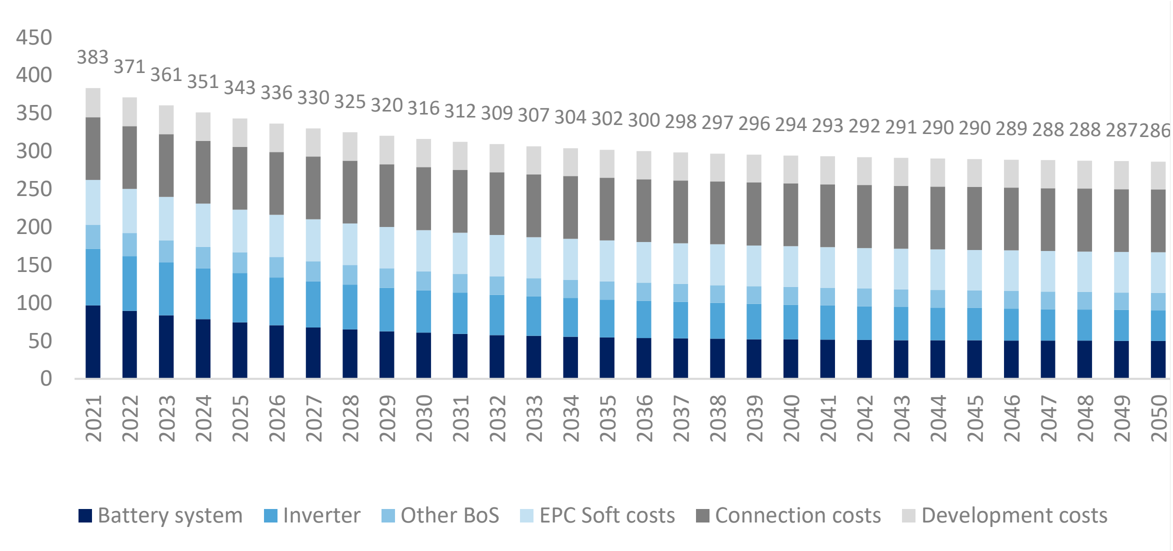


Figure 12: BESS cost estimations 2021-2050 for 1 h battery systems

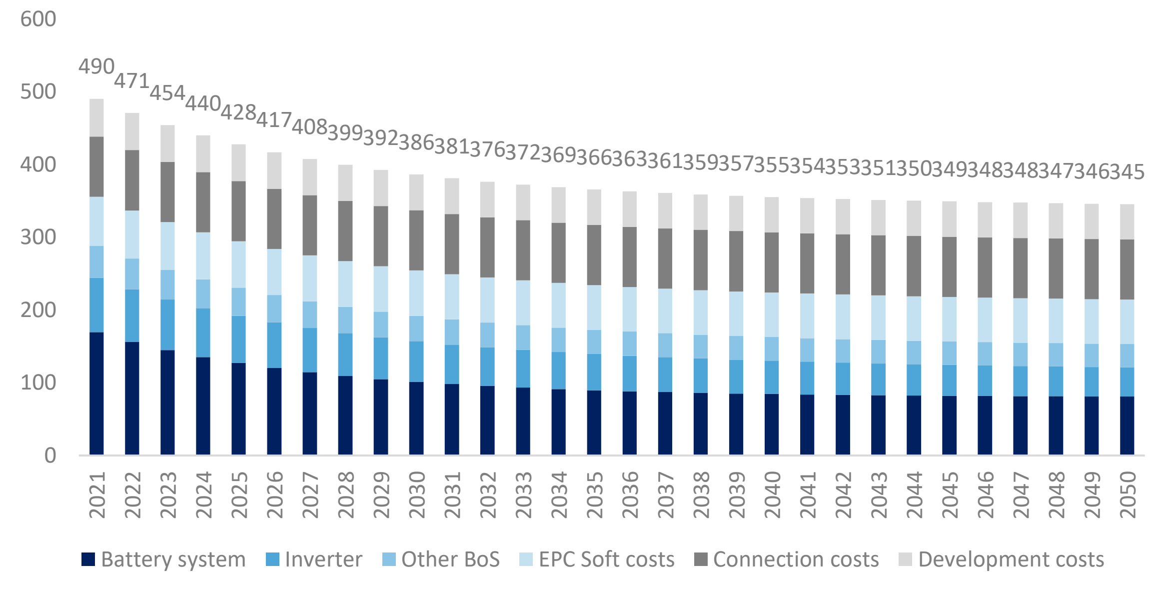
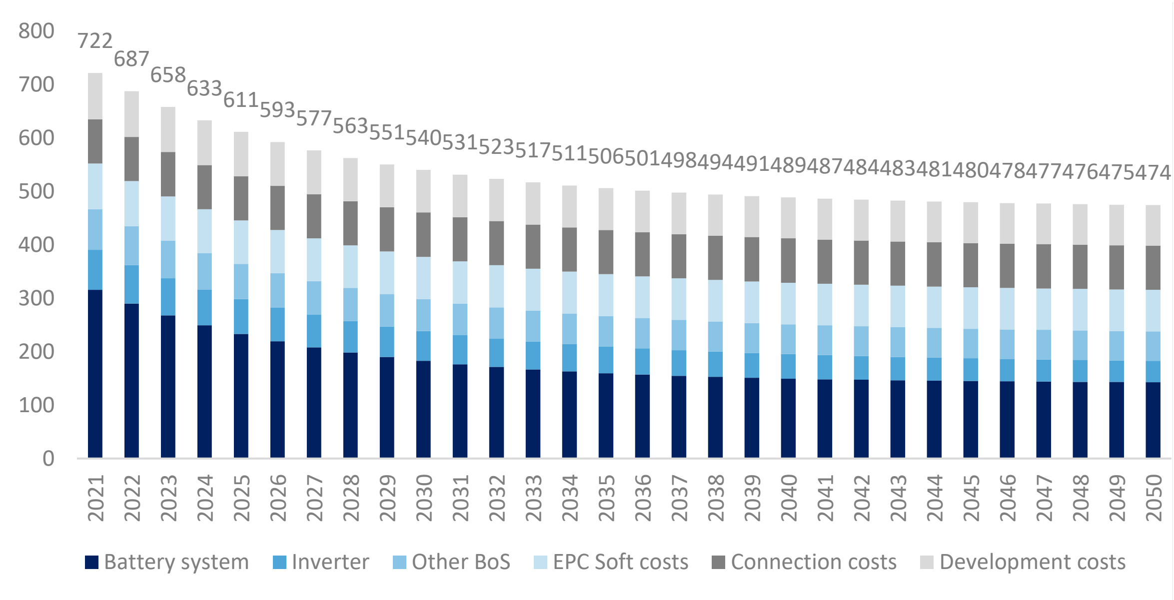


Figure 13: BESS Cost estimations 2021-2050 for 2 h battery systems



PART 2. BATTERY ENERGY STORAGE SYSTEMS: A PROMISING OPPORTUNITY TO ENABLE THE ENERGY TRANSITION IN TUNISIA

1 Overview of the energy sector in Tunisia

The energy situation in Tunisia is currently characterized by several factors. The primary source of energy in the country is natural gas, which accounted for 49% of total demand in 2021, followed by petroleum products at 40%. Given its limited primary energy resources, Tunisia has therefore registered a primary energy deficit of 4.1 MTOE at the end of October 2022 compared to a deficit of 3.7 MTOE at the end of October 2021. In 2020, energy production in Tunisia decreased mainly due to a decline in the national production of crude oil. However, despite an increase since 2011, the primary energy demand stabilized at 8 MTOE between the end of October 2021 and the end of October 2022.

The energy independence rate, which represents the ratio of national primary energy resources to primary consumption, decreased from 53% at the end of October 2021 to 49% at the end of October 2022. The share of natural gas increased at the expense of other forms of energy following the commissioning of several gas and oil fields: "Nawara" gas field in March 2020, "Halk El Menzel" oil field in January 2021 and "Sidi Marzoug" and "Chalbia" fields in October 2021. The "Nawara" gas field alone represented 30% of national commercial gas production and resulted in a 15% increase in the production of natural gas.

Figure 14: Primary Energy Deficit (MTOE)

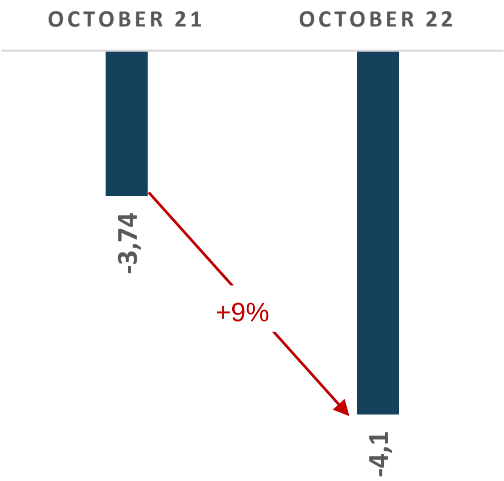


Figure 15: Independence rate (%)

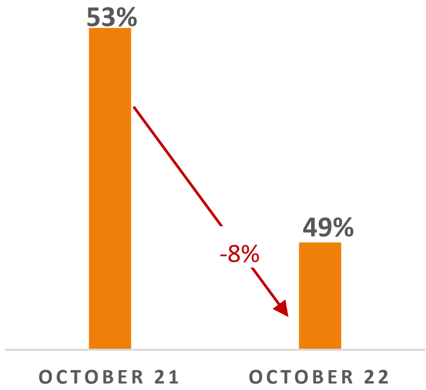
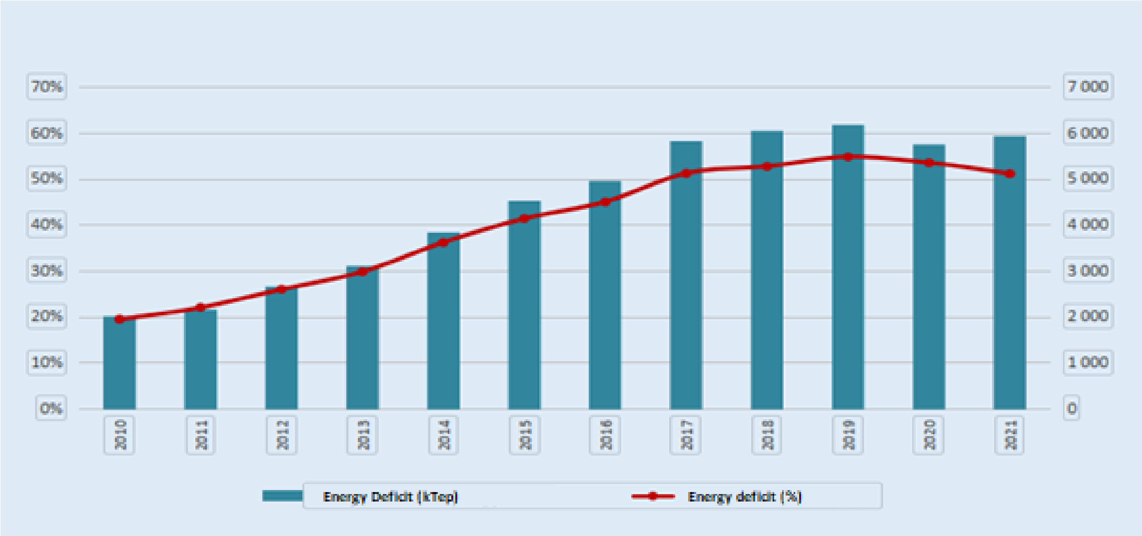
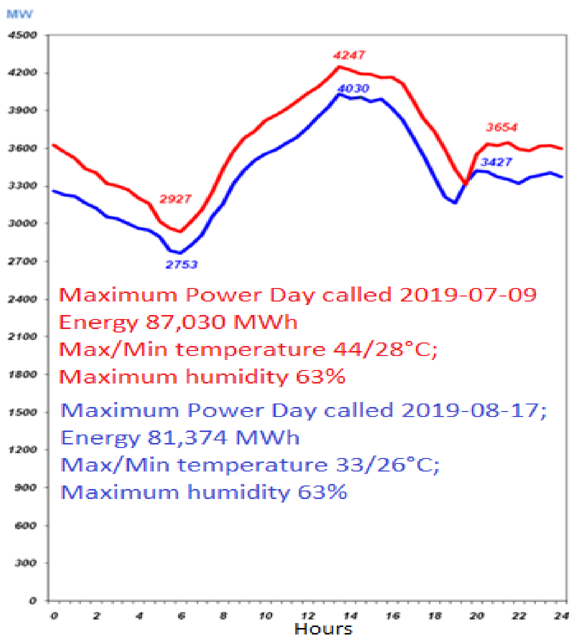


Figure 16: Progress of the energy deficit 2010-2021[25]



The consequences of the COVID-19 pandemic on Tunisia's energy sector were most acute immediately following the outbreak, though gradually eased as the year progressed. The country's energy accounts featured a modest improvement in the deficit for 2020 compared to 2019 subsequent to years of gradual worsening due to falling demand.

Figure 17 The impact of Covid on Tunisian load Curve 2020 Vs 2019



The energy gap thus narrowed from 54.8% in 2019 to 53.6% in 2020 (it was only 20% in 2010. In 2021) the deficit continued improving, reaching 51.3%, though consumption rose due to higher output. The persisting deficit reduction indicates positive development, but the large gap between production and consumption and reliance on imports remain a real challenge for the country's energy system.

The Tunisian Electricity and Gas Company (STEG), the nation's primary utility, witnessed electricity demand fall by 20% year-on-year in April 2020 - representing 60 to 65% of total demand from industry,

[25] Unless otherwise stated, the images are sourced from *Annual report of National observatory of Energy and Mines, 2022*.

services and agriculture. As an outcome, STEG was compelled to postpone certain renewable energy initiatives, attributable partly to supply chain disruptions and labour mobility restrictions.

Despite previous financial issues mainly due to clients' debt,[26] the abrupt drop in energy consumption severely impacted STEG's revenues while delays to renewables projects hindered Tunisia's clean energy transition plans. However, as demand started to recover from the subsequent month onwards, STEG recouped some losses during the second half of 2020.

Together with COVID-19, the international energy crisis changed the energy landscape in Europe and the Mediterranean. Before the invasion, Russia dominated European gas supply pipelines, exporting around 40% of total imports to the 27 member states of the European Union. Following the Ukraine invasion and ensuing disruptions, Europe has turned to liquefied natural gas (LNG) from the U.S. shale gas industry to bolster energy security. The EU-US agreement signed March 2022 aims to deliver 15 billion cubic meters extra U.S. LNG this year, increasing by 70%, reaching 50 billion thereafter until 2030. Correspondingly, Europe plans to build 32 new LNG import terminals to guarantee LNG volumes in coming years.

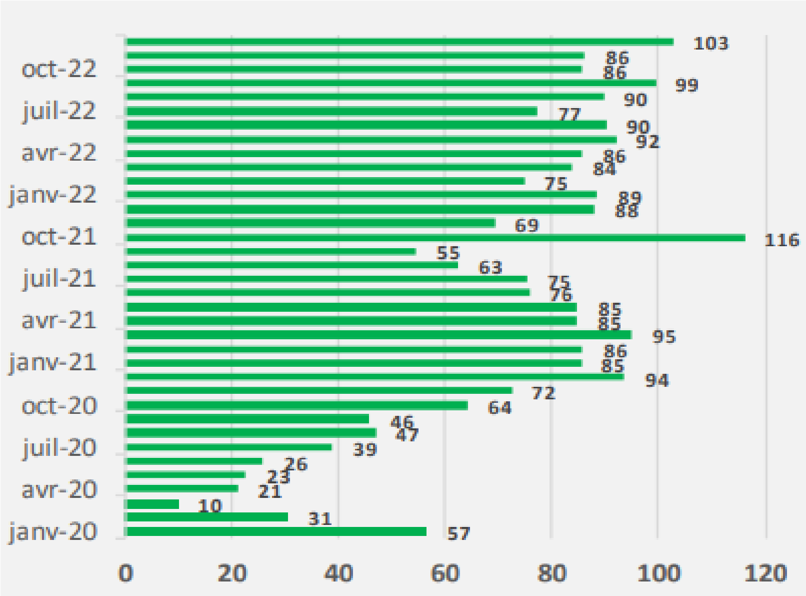
The goal is to become independent from Russia by 2027. Between January to November 2022, Russian pipelines and LNG comprised under 25% of European imports, with Norway supplying nearly 25% and Algeria around 12%. The remaining 25.7% (minus Russian LNG) was LNG primarily from the U.S., Qatar and Nigeria as per European Commission data. However, LNG produces twice the emissions of pipelines according to Carbone4 research. Meanwhile, electricity operators recommend boosting clean power: solar and wind outpacing fossil fuels.

The agreement signed in 2022 in Algiers by Italian Prime Minister Mario Draghi and Algerian President Abdelmadjid Tebboune, stipulating a progressive raise by 40% until 2024 of the gas volumes transiting the Transmed pipeline, has been seen as an unforeseen source of income for the country. The additional gas volumes planned through Transmed will likely translate into higher transit fees and royalties for Tunisia, helping boost public revenues. The Transmed pipeline is a crucial piece of energy infrastructure for Tunisia. By transmitting Algerian natural gas across Tunisian territory for 400 kilometers before reaching Italy, the pipeline generates significant transit fees and royalty payments paid in kind for Tunisia each year (see Figure 18). These revenues play an important role in Tunisia's energy sector finances and balance of payments. Furthermore, Tunisia has access to some of the gas from Transmed via a lateral pipeline. This provides around 10% of Tunisia's natural gas demand, helping reduce the country's reliance on imported liquefied natural gas. The royalties brought 500 MD to Tunisia in 2022 according to the Ministry of Industry, Mines and Energy and 65% of the country's energy needs.

[26] Please see https://www.tustex.com/economie-actualites-des-societes/tunisie-la-situation-financiere-de-la-steg-extremement-inquietante.

Nevertheless, the 2022 budget was estimated on the basis of a barrel price of 75 dollars (on average over the year). Currently is close to 110 dollars. A one-dollar rise in the price of a barrel of oil costs the state about 140 million dinars (43.3 million euros), especially since significant foreign exchange resources will now be devoted to energy imports.

Figure 18: Algerian Gas tax package (ktep-pci) Year 2020-2022

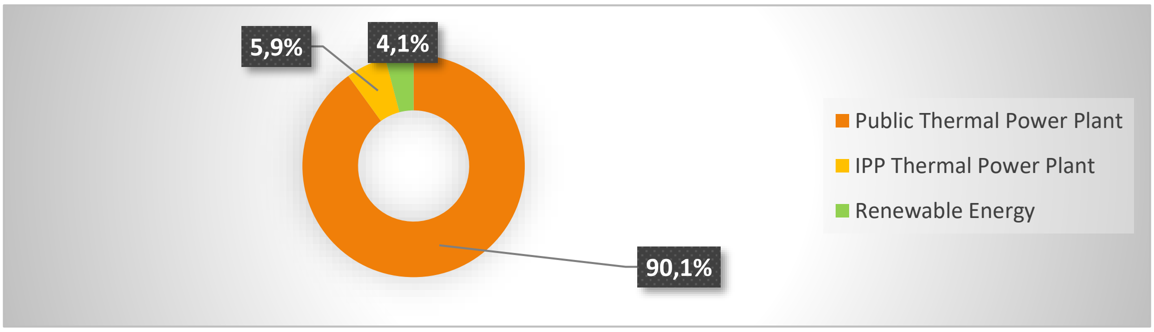


Despite the willingness to diversify the energy mix since 2004, currently the electricity mix is dominated by gas-fired thermal power plants, which account for 92% to 97% of the total generation capacity. Renewable energies play a modest role in the overall electricity mix and are heavily reliant on the fluctuating contribution of hydropower. The share of renewable energies in electricity production has slightly increased from 3.9% to 4.1%, mainly due to the growth of solar PV among self-producers (residential and industrial). Large scale Solar Power plants contribute to an extent limited to 1.8% of the national production.

Figure 19: Generated Power (GWh) by power plant

Power Plant	Generated Power				
	2017	2018	2019	2020	2021
Renewables	467	470	566	511	465
Combustion Turbine	2890	2812	3362	3956	4350
Combined Cycle	9726	9664	10260	9513	10288
Steam Turbine	2348	2770	2819	2183	1618
IPP Rades	3543	3374	3071	3145	3138

Figure 20: Electricity generation by type production[27]



Concerning the electricity consumption of the main economic sectors in Tunisia shown in Table 11, industry emerges as the heaviest consumer of power, accounting for 59% of total demand from HT and MT customers (high and medium tension) as of end-October 2022, followed by services, sanitary services, agriculture, tourism and transportation.

Table 11: Details of HV-MV consumption

Sector	Electricity Consumed (HV-MV)		
	Year	2022	2021
Industries	Share of energy consumed	59.9%	61.4%
	Consumption in GWh	12418	12458
	Number of Consumer	5052	4993
Agriculture	Share of energy consumed	8.3%	8.6%
	Consumption in GWh	1716	1747
	Number of Consumer	698	700
Pumping and Sanitary services	Share of energy consumed	10.5%	10.7%
	Consumption in GWh	2183	2178
	Number of Consumer	888	872
Transportation	Share of energy consumed	3.2%	3.2%
	Consumption in GWh	666	644
	Number of Consumer	271	258
Tourism	Share of energy consumed	6%	4.1%
	Consumption in GWh	1241	841
	Number of Consumer	505	337
Services	Share of energy consumed	12.1%	12%
	Consumption in GWh	2512	2440
	Number of Consumer	1022	978

[27] (ONEM, 2023).

1.1 The electricity sector

1.1.1 The national electricity grids

Between 2015 and 2021, Tunisia witnessed significant growth in its medium and low voltage power distribution networks. Specifically, the length of medium voltage lines (which range from 1 kV to 35 kV) increased by 25% over this period, reaching 63,000 kilometres in 2021. This expansion is aimed at strengthening the distribution network and improving access to electricity across the country. The length of low voltage lines - under 1 kV - also grew markedly, rising 37% to reach 123,156 kilometres in 2021. The rise in low voltage infrastructure helps deliver electricity to households and local businesses. However, the total length of high voltage transmission lines remained unchanged at 6,793 km.

Figure 21: Electricity Grid: Distribution Network

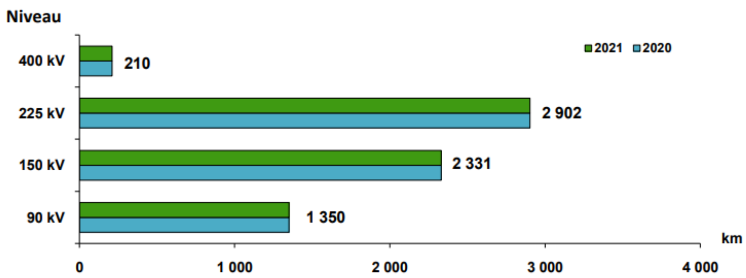


Figure 22: Map of Transmission lines, Power Plants, and Substations[28]

1.1.2 The renewable energy framework

In December 2022, Tunisian Ministry for Energy, Mines, Renewable Energy launched two tenders to deploy 1.7 GW of solar capacity and 600 MW of wind power will be added to the grid. Projects will take place between 2023 and 2025. This is in line with the Tunisian Solar Plan in 2009 (updated in 2012) with a long-term objective to achieve 3.8 GW of renewable energy capacity by 2030. To achieve these objectives, the government has passed various laws and incentives to speed up renewable energy development.

[28] See https://www.steg.com.tn/$J@5cxwQEhCgOhAtbABijVdXAVATyTHuzxrTkh15tw4dsBTfbFEbT65b8k?tknfv=%3Edffa4324-46b0-46ef-a52d-f9e64d3e1poj1pj

The fundamental text related to renewable energy is Law N° 2015 12. This Law, which was adopted on May 11th, 2015, created a framework for the legal regulation of the development of renewable energy projects. It outlines the project development framework and the National Plan for the production of electricity from renewable resources.

Table 12: Major policies and incentives for renewable deployment in Tunisia

Policy	Content
Decision supplementing Law 12.2015 (2017)	• Establishes the specifications for connection to the grid • Defines the contract for self-consumption in low voltage (net metering), in medium and high voltage • Establishes the PPA contact for the authorisation scheme
Decree 983.2017 on Energy Transition Fund (2017)	• Funds amount to 100 million Tunisian dinar (Ministry of Finance 2018) through loans (to date not operational) subsidies (through ANME) • Primarily intended for commercial companies with the objective to reduce their energy bill • Non-profit projects for renewable generation of electricity under self-consumption can benefit from this fund
Law 71.2016 in Investment Fund (2016)	• Establishes the Tunisian Investment Fund • The resources of the Fund consist of State resources, loans and grants from within and from abroad and all other resources • The interventions consist in granting subsidies for the execution of direct investment operations in key sectors including RE and equity contributions • Establishes the facilities for projects of national interest (Decree 398-2017) • A deduction of profits from the corporate tax base within the limit of ten years • An investment premium in the limit of one third of the investment cost including the expenses of intramural infrastructure works with a cap of 30 million dinar • State participation in the expenses for infrastructure works
Decree 1123.2016 (2016)	• Sets the conditions and procedures for the production and sale of electricity through renewable energy sources (self-generation) • amended in 2020
Law 12.2015 (2015)	• Distinguishes three main support mechanisms for renewable energy projects: ▪ generation for export (currently not applicable) ▪ self-consumption, sale and surplus ▪ generation to meet domestic needs under a PPA • Tunisia's PPAs fall into two groups: a) the authorisation regime, covering projects below 10 MW for solar and 30 MW for wind, awarded through simple tenders; and b) the concession regime, covering projects over 10 MW for solar and over 30 MW for wind, awarded via competitive concessions • The Law clearly states that foreigners are not allowed to buy or take

Policy	Content
	advantage of agricultural land, unless leased • Provides the right for companies adopting renewables for self-production to sell electricity to other consumers or companies with subscribed power greater than the threshold set by MEMTE electricity 30% and use the national grid network to transport electricity
Renewable Energy Law on electricity production Law 74.2013 (2015)	• Encourages investment in renewable energy towards increasing the contribution of renewable energy electricity to 30% equivalent to 3.8 GW of total electricity production by 2030 • Boosts investments in the electricity sector, creates 10 thousand jobs and reduces the debt of STEG
Tunisian Solar Plan (published in 2009 - revised in 2012- Revised in 2022)	• national program aiming at reaching the renewable energy development strategy targets • aims to achieve 3.8 GW of renewable energy capacity by 2030, 35% in power generation
Law 7.2009 on Energy Efficiency and RE provisions (2009)	• Authorises energy companies producing electricity from co-generation to sell their production to the public utility STEG and transport it through the national grid • Allows any establishment, or group of establishments in the industry, agriculture and services, to produce electricity from energy saving, co-generation or renewable energy (including self-generation), and to sell it to STEG (limited to 30% of the energy production)

Other policy instruments include:

- Order of the Head of Government of December 26, 2022, authorizing the construction and operation of a 225 kV high-voltage overhead power line connecting the Metbasta photovoltaic power station via the existing Oueslatia - Msaken line.
- Presidential Decree No. 2022-299 of March 28, 2022 on the exceptional extension of 20 additional months of the deadlines for agreements in principle (authorization regime),
- Order of the Minister of Industry, Mines and Energy dated 17 November 2022, fixing the minimum power of electricity self-production projects from renewable energies connected to the high and medium voltage network subject to the agreement of the Minister responsible for energy.
- Decree-Law No. 2022-68 of October 19, 2022, enacting special provisions for improving the efficiency of the implementation of public and private projects.
- Law No. 2019-47 of May 30, 2019 on improving the investment climate (articles 7 and 8).
- Order of August 30, 2018 (Approval of the PPA model contract revised authorization regime).
- Order of 09 February 2017 (Approval of the LV connection specifications).
- Order of 09 February 2017 (Approval of the HV/MV connection specifications).
- Order of 09 February 2017 (Approval of the standard BT self-production contract).

- Order of February 9, 2017 (Approval of the standard HT/MT self-production contract).
- Order of 09 February 2017 (Approval of the PPA standard contract authorization scheme).
- Decree No. 2017-389 of March 9, 2017 (FTI incentives).
- Decree No. 2017-191 of January 25, 2017 (Tax incentives).
- Decision of June 1, 2014 (Tariff for the transport of self-consumed energy and the purchase of surpluses).
- Law No. 2013-54 of December 30, 2013 relating to the finance law of 2014 (articles 67-68) as amended by law No. 54-2014 relating to the complementary finance law of 2014 (article 3) (Creation energy transition fund).
- Decree No. 1996-1125 of June 20, 1996 (Modalities for granting concessions to private persons).
- Law N°1996-27 of April 1, 1996 (Granting of concessions to private persons).

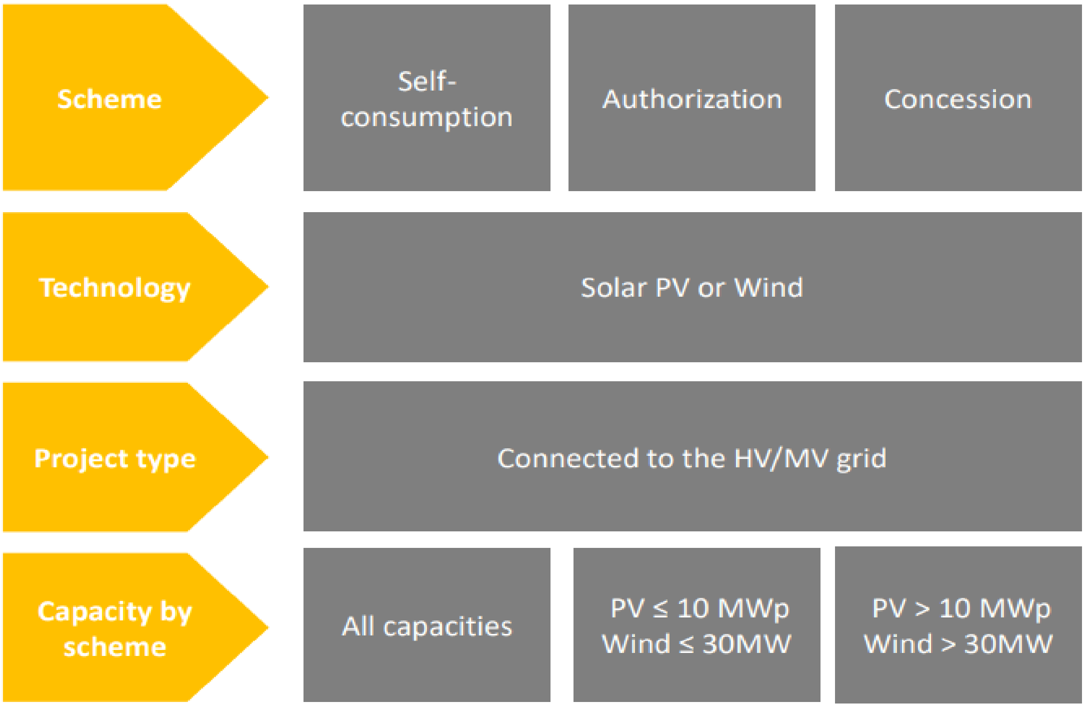
As shown in Figure 23, the three resulting power generation regulatory schemes are:

- **Self-consumption (HV MV)**: Any local authority and any public or private entity, connected to the national electricity grid in MV or HV [29]and operating in the sectors of industry, agriculture or the tertiary sector can produce its own electricity via renewable energy sources. Self-consumption projects provide the possibility to consume one's own produced electricity instantly, thus saving money on electricity bills, and the possibility to sell the excess electricity generation to the STEG, which commits to purchasing the excess electricity as part of a contract between the two parties (up to 30% of the annual generation of the installation). This excess electricity purchase agreement is signed for a period of 20 years, and is automatically renewed for a period of one year, unless terminated by one of the parties. Sales tariff of surplus production differs according to the hourly period.[30]
    - On site (without power wheeling)
    - Off site (remote site), with power wheeling subjected to a fee
    - The total and exclusive sale of the power to the STEG to satisfy national demand.
- **Authorisations scheme**, below a given capacity limit: Capacity <10 MW for solar Power Plant and Wind Power Plant <30 MW Any entity, any local and international investor and any independent producer wishing to develop a renewable energy project intended to satisfy the needs of the Tunisian consumption can present a request in order to obtain a preliminary Ministerial agreement (“accord de principe”) for the realization of their project, then sell the electricity to the STEG. This system is subject to an authorization issued by the Ministry of Energy on the notice of the technical commission, within the limit of a maximum installed capacity. The granting of authorizations comes in the form of a call for projects and in accordance with the annual notice issued by the Ministry of Energy specifying the national requirements for the generation of electricity from renewable energies

[29] There is also the possibility for STEG customers connected to the LV grid (which have different conditions) to sell their electricity.
[30] For LV projects, the contract is for 1 year with a tacit renewal of 1 year.

- **Concessions scheme**, above a given capacity limit: Capacity >10 MW for solar Power Plant and Wind Power Plant >30 MWc: projects shall be subject to a public tender procedure by the State and that the various conventions relating to the grant of each project need to be approved by a special committee at the People's Assembly (ARP).
- Export scheme: it's a specific case of Concession destinated to electricity exportation (not used so far).

Figure 23: Technical framework for renewables power plants[31]



Despite having a wealth of resources, Tunisia only has a small number of operational plants producing power from renewable sources. The following is a summary of the major accomplishments at the end of 2022.

Table 13: Renewables Projects

Source	Regime	Projects	Status
Solar PV	STEG	Tozeur1: 10 MWp	Commissioning Date: 03/10/2021(8MW) Start operation date: 04/12/2022
		Tozeur2: 10 MWp	Commissioning Date: 24/11/2021 Not Operational

[31] Summary Guide-Ministry of Energy.

Source	Regime	Projects	Status
	Self-consumption	LV	168 MW
		MV/HV	304 permits granted for a total capacity of 79 MW.
	Authorization	1st Tender Round (2017)	• Award of 10 authorization (4 projects category 1MW + 6 projects category 10MW) • Creation of 7 project companies • Commissioning of one 1MW project + one 10MW project
		2nd tender Round (2018)	• Award of 16 agreements in principle (10 projects category 1MW + 6 projects category 10MW) • Creation of 5 project companies • No Realisation
		3rd Tender Round (2019)	• Award of 16 agreements in principle (6 projects category 10MW + • 10 projects category 1MW)
		4th Tender Round (2020)	• Award of 16 agreements in principle (6 projects category 10MW + • 10 projects category 1MW)
	Concession	1st Tender Round: 2018	500 MW: (sites proposed by State): • 50MW Location: TOZEUR • 50MW Location: SIDI BOUZID • 100MW Location: GAFSA, • 100MW Location: KAIROUAN • 200MW Location: TATAOUINE Only one project of 100 MW is under financial closure (KAIROUAN SITE).
		2nd tender Round: 2023-2025	800 MW (Private Sites): broken down into 8 projects of 100MW each: Agenda: • 1st round: 15 June2023 • 2nd round: March 2024 • 3rd round: November 2024 • 4th round: September 2025
			2 Plants (Public sites): 18 May 2023 Public Sites: • 300 Ha à HECHA (GABES) • 270 Ha à KHOUBNA (SIDI BOUZID)
Wind	STEG	SIDI DAWED: 55 MW	Year of Commissioning: 2009
		Mételine: 97 MW	Year of Commissioning: 2012/2015
		Kachbata: 93 MW	Year of Commissioning: 2012/2015

1.1.3 Main stakeholders

Several stakeholders are involved in the energy sector in Tunisia, including the government, private energy companies, and consumers. However, one of the most influential stakeholders in the Tunisian energy sector is the government, Within the Ministry of Energy and Mines, the **Electricity and Renewable Energy General Directorate** (DGEER) is in charge of issues relating to renewable energy. This entity publishes the different calls for Project and tenders in the sector. The Ministry grants the authorization following the CTER’s notice.

The National Energy Management Agency (ANME) designs and promotes energy efficiency and renewable energy development programs. Its mission consists in implementing the energy management State policy, and thus, the promotion of energy efficiency, renewable energy and energy substitution. The ANME is in the charge of the Energy Transition Fund (FTE) subsidies grants for self-consumption projects.

The Tunisian Company of Electricity and Gas (STEG) is the historical electricity utility in Tunisia. Initially a vertically integrated monopoly, it is today a dominant energy producer, the unique purchaser of all power produced in Tunisia and has a monopoly on transmission, commercialisation and distribution of electricity in Tunisia. It owns an installed capacity of 4 838 MW (2017), which represents 91.1% of the total installed capacity in Tunisia.

The Technical Commission of private renewable power generation (CTER)’s mission is to provide an opinion on authorization project requests, as well as on the extension and the withdrawal of the authorization, and to study all issues related to renewable energy development submitted by the Ministry, as well as on concession projects. The CTER is composed of representatives from several Ministries, the STEG and the ANME.

The Specialized Authority handles issues and claims relative to projects developed within the framework of law n°2015-12: the rejection or withdrawal of the Ministry approval and authorization, the disputes between the project company and the STEG regarding the execution or the interpretation of the power purchase contract. The Specialized Authority is led by a judge and is composed of representatives from the Government Presidency, from Ministries and electricity and renewable energy experts.

As for the private sector, the Syndical Chamber of PV Integrators (CSPV) CSPV is a Trade Union of the Photovoltaic Industry representing the photovoltaic integrators in Tunisia whose mission is to defend the interests of its members and to promote the solar PV market. It is affiliated to the UTICA and has been established in November 2015.

2 Benefits of BESS systems for the Tunisian network

Building upon the comprehensive analysis of energy storage technologies presented in previous chapters, this section focuses on the specific benefits that Battery Energy Storage Systems (BESS) can bring to the Tunisian network. As Tunisia strives to diversify its energy mix and integrate a greater share of renewable energy, the need for innovative solutions to address the challenges of intermittency and grid stability becomes paramount. By examining the advantages of BESS in the Tunisian context, the following aims to provide valuable insights into the potential role of energy storage systems in facilitating a sustainable and resilient energy transition in Tunisia.

Renewable energy integration stands as a key challenge for Tunisia's energy sector. The inherently variable nature of renewable sources, such as solar and wind, necessitates flexible and reliable solutions to ensure a stable power supply. BESS systems offer a unique opportunity to mitigate the intermittency issues associated with renewable energy generation. By storing excess energy during periods of high production and discharging it during periods of lower supply, BESS can effectively balance supply and demand, contributing to grid stability and enabling a higher penetration of renewables. Additionally, the deployment of BESS in close proximity to renewable energy plants allows for optimal utilization of available resources, reducing curtailment and maximizing the value of renewable assets and increasing utilization factor of the grid infrastructures.

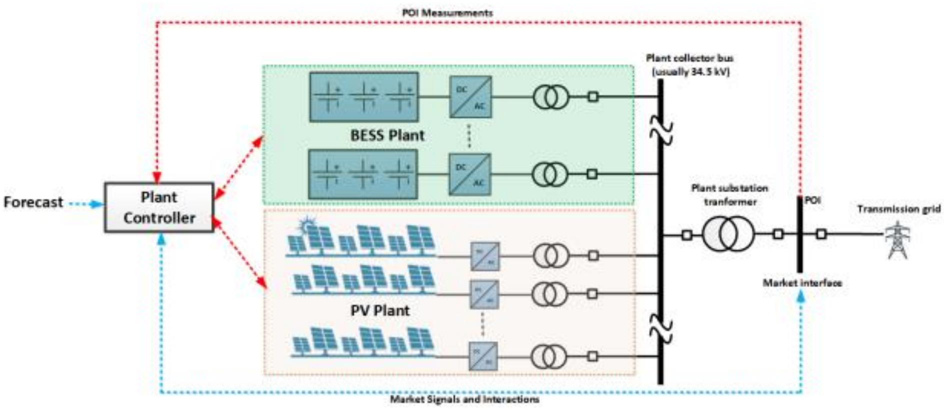
In addition to addressing renewable energy integration challenges, BESS systems can also offer economic advantages to the Tunisian energy sector. The declining costs of battery technologies, coupled with the increasing deployment of renewable energy, create favorable conditions for the widespread adoption of BESS in Tunisia. By optimizing the use of renewable energy resources and providing grid support services, BESS can enhance the overall efficiency of the energy system, reduce reliance on conventional generation, and contribute to cost savings. These economic benefits align with Tunisia's ambitions to achieve energy security, affordability, and sustainability, making BESS a promising enabler of the country's energy transition.

2.1 Integration of renewables and stabilisation of the electricity system for the large-scale introduction of variable renewable sources

BESS can efficiently use solar and wind energy at any time. Rechargeable batteries can store excess energy generated by intermittent renewables. Later, this energy can be distributed according to user needs. When coupled with battery storage solutions, renewable energy sources can replace fossil fuels, providing clean energy for a variety of applications. BESS applications can be considered for the following assets:

- Solar and wind farms under concession and authorization scheme: as mentioned earlier, for authorization systems with a capacity of 1MW and concession systems ranging from 10 MWc to 100 MWc, there will be a requirement to install BESS with a capacity equivalent to 20% of the total power of the plant.[32] According to the Ministry of Energy, the estimated potential of BESS for large-scale projects under the concessions scheme is approximately 2 GWh for the period between 2025 and 2035.
- The PROSOL ELEC program is a part of the National Energy Management Program in Tunisia, aimed at customers who wish to purchase a photovoltaic (PV) solar installation to meet their electricity needs. It was launched in 2010 and serves as a support mechanism for the diffusion of photovoltaic systems in the low voltage residential sector (LV), ranging from 1 to 3 KWp. The program is based on self-consumption with a net-metering tariff type, and it provides consumers a credit over 7 years. Currently, there is no interest in investing in storage for the residential sector, as the payback time is less than 5 years and net-metering is used to develop solar roofs. However, there is a need for storage for large residential consumers who require PV installations with back-up. The new renewable energy code is set to launch in 2024, and from 2025, net-metering will be scrapped. The market is expected to reach about 50,000 solar rooftops per year, with an estimated PV capacity of 100 to 150 MWp/year by 2025. The BESS market share is estimated to be at 10%, i.e., 10 to 15 MWp, which will be with storage systems. By 2027, the storage capacity is estimated to be 30 to 45 MWh/year (for storage of 3h/day). This market will develop quickly by 2030, following the installation of 4 million smart meters with hourly tariffs (4 to 5 tariffs per day). Subscribers can use batteries between 7 p.m. and 10 p.m. in the evening.
- BESS can be used in on-grid solutions for residential, commercial, and industrial use. In August 2022 STEG started to authorize the installation of hybrid inverters for grid-connected systems. The use of hybrid systems is not yet approved, the law overseeing this process will be issued in the near future.

Figure 24: PV Plant-BESS system



[32] However, no information about the duration is available.

In the case where photovoltaic energy has a high penetration rate (around 30% in energy) and/or conventional flexibility is not or hardly exploited because of technical limitations, the need for storage solutions becomes effective (as of the 35% RE scenario).

2.2 Regulation of frequency and voltage fluctuations

In recent years, variable renewable energies (VRE), such as photovoltaic (PV) and wind turbines (WT), whose energy output fluctuates greatly, have been introduced worldwide. On the existing Power Systems, the frequency fluctuation becomes excessive. The frequency fluctuation is mainly caused by:

2.2.1 Frequency fluctuation of the power system

If variable renewables, a fluctuating generation output (photovoltaic (PV) and wind (WT)), connects massively to the power system, as expected in Tunisia in the next years, the output power fluctuation will overlap with the system load fluctuation, which will result in a larger load fluctuation and an increase in the frequency fluctuation. In order to check the frequency fluctuation when a large number of VREs are connected to the power system, the inputs below are important to calculate the frequency fluctuation over a short period of time under normal conditions.

- Value of the fluctuation of the electrical load
- Value of the PV & WT output fluctuation

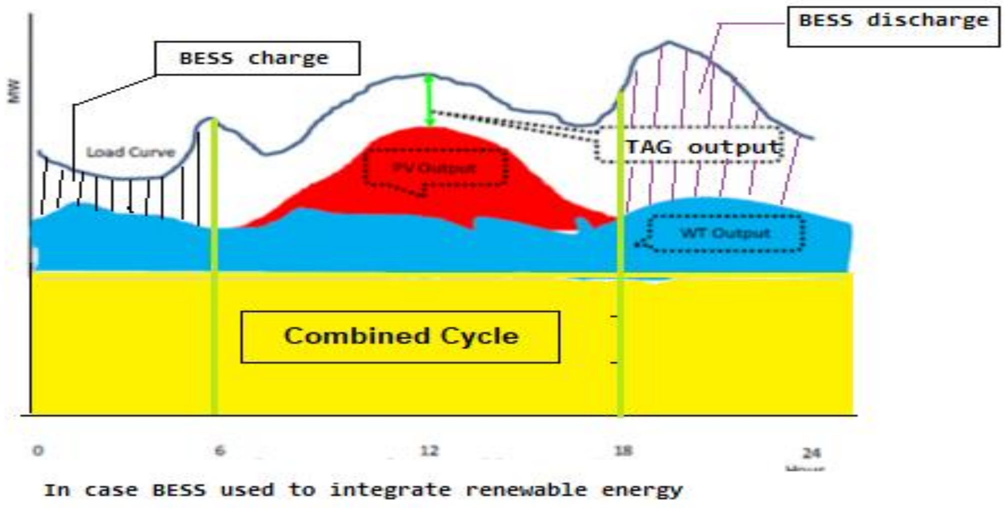
To obtain accurate quantitative results, it is necessary that these values are within a reasonable range. Of course, if these values are high, severe results will be obtained. However, now it is difficult to predict these sizes accurately in the future. Therefore, to avoid underestimating the risk of increasing frequency fluctuation, adjusting the power load fluctuation and VRE output fluctuation to some extent is considered a rational choice.

2.2.2 Decrease in thermal power plant output

When a large number of VREs are connected to the grid, the output of thermal power plants (CC+GT), which have the function of frequency control, must be suppressed in order to balance supply and demand, and the ratio (%) of thermal power generation to grid capacity decreases. As shown in the following figure, the output of the thermal power generator (CC+GT) decreases as the PV and WT output increases.

$$\text{Demand load} = GT+CC + PV + WT + BESS$$

Figure 25: Load curve with BESS integration[33]



During weekends, the power demand load decreases, and the PV (+ WT) output is large, so the ratio of GT+CC output decreases and the frequency control capability decreases. Therefore, it is assumed that the risk of increased frequency fluctuation increases during weekends, as the load is low on weekends due to the closure of some industries. Additionally, inertia decreases when fewer thermal generators are online, accelerating rate of change of frequency that can be compensated by BESS fast response and synthetic inertia.

2.3 Strengthening the cross-border interconnections

Interconnections and BESS are two complementary elements in the context of the electrical grid. The first enhances reliability and flexibility, the second provides a means of storing electricity, which can be utilised to balance supply and demand, improve grid stability, and integrate renewable energy sources effectively. Together, interconnections and BESS work synergistically to optimise grid operations, enable efficient energy management, and facilitate the integration of renewable energy into the grid.

This is why strengthening the international interconnections is an effective way to deal with the frequency fluctuation problem related to the massive introduction of VRE, but the political risks must be considered. Firstly, from the point of view of energy security, it is important to ensure the country's frequency adjustment capacity. Although there are two interconnection systems with Algeria and Libya, the interconnection with Libya is no longer functional and the use of the interconnection between Algeria has been relatively low. The exchange capacity is 800 MW, the call on this interconnection last year was 200 MW.

[33] Authors' elaboration.

Figure 26: North Africa Electrical Interconnection

Within the framework of the Tunisia Solar Energy Program, the ELMED (Electricity Mediterranean) project with a capacity of 600 MW (submarine cables, HVDC) to be realised before 2030 for a total amount of €800 million was announced between STEG and Terna. The EU granted access to a fund for Tunisia of about €307.6 million to finance a part of the cable linking Tunisia and Italy.

The plan included two projects, a 200-kilometre high-voltage direct current (HVDC) submarine line linking Cap Bon in Tunisia and the island of Sicily in Italy, and a 1,200 MW power plant on the Tunisian side. Due to the difficulty of implementing the plan within a reasonable timeframe, it was revised into a simpler plan abandoning the construction of a 1,200 MW power plant and maintaining the 600 MW HVDC line jointly financed by Tunisia and Italy. The World Bank, which plans to finance the project, mobilised funds for the feasibility study in 2018.

The 600 MW will be operational by 2027, and this capacity will be doubled (1200 MW) from 2030. This project will allow peak shaving and load curve shaving, as well as the evacuation of energy peaks and dealing with intermittency.

2.4 BESS for household self-consumption (LV network)

There is a beneficial relationship between the demand for electricity and its cost, where the price of energy increases during peak periods and decreases when demand is low. By charging their battery during off-peak times, consumers can purchase energy at the lowest cost and store it with their BESS. They can then wait for the price of electricity to rise and discharge the battery to either use low-cost energy or sell it back to the grid. This allows households and businesses to manage their energy resources efficiently, reducing overall costs.

Additionally, electric vehicles can be charged through the smart grid during off-peak hours and peak sunlight, further maximizing the benefits of energy storage. Currently, LV metering is very favourable with net-metering allowing partial compensation of electricity consumption billed by the production of an installation on the consumption site. STEG plays a role in storage on their network, but the law will change once smart metering is implemented, creating an interesting market (50MW from 2030).

2.5 BESS for industrial self-consumption (MV network)

The integration of battery energy storage systems (BESS) for medium voltage industrial customers offers several potential benefits:

- Overcoming Article 2 constraints: BESS can absorb excess electricity generated from onsite solar PV that exceeds the 30% net-billing limit. The hybrid inverters ensure surplus power from renewables is stored instead of curtailed or sold at low tariffs.
- Reducing energy costs: BESS allows industries to store solar power during the day and use it later to offset grid purchases, lowering total electricity bills.
- Improving stability of supply: BESS provides a reliable power source for industries during grid outages or disruptions, lowering risks.
- Unlocking new revenue streams: BESS combined with solar PV and hybrid inverters enables industries to provide grid services like frequency regulation and capacity market participation, generating additional revenues.
- Promoting energy transition: Widespread adoption of BESS by industries will support the integration of higher shares of renewables into Tunisia's energy mix.

The falling costs of lithium-ion batteries and growing industrial energy demand point to significant potential for BESS deployment in Tunisian industries over the coming years. Carefully structuring public-private partnerships and incentive schemes can help accelerate the pace of installations.
With the right policy enablers, BESS could emerge as an important tool to optimize Tunisia's industrial electricity consumption by 2035 and beyond. Based on the available data and assumptions, the estimations for potential battery energy storage deployment in Tunisian industries appear in the order of 720 MWh by 2035 translates to an average annual growth of around 72 MWh, starting from 2025. Some key considerations include:

- The estimated storage capacity represents a gradual but orderly ramp-up that allows the market to develop properly over time.
- The estimation is tied to industrial electricity consumption trends, which are expected to continue rising given Tunisia's economic growth trajectory. Since industries account for over 60% of total power demand, there is ample opportunity for storage to optimize this usage.

- The falling costs of lithium-ion batteries and growing customer experience with storage solutions will make such installations increasingly attractive for Tunisian industries through 2035. However, government support in the form of incentives, tax breaks and enabling infrastructures will still be needed.
- Accurately estimating storage potential by 2035 involves many uncertainties. The figure of 720 MWh should thus be considered a rough order-of-magnitude estimation based on reasonable assumptions. The actual deployment will likely depend on a host of dynamic market and policy factors.

In addition, the EU is planning to implement a CBAM starting in 2026 that will impose carbon costs on imports of certain carbon-intensive goods like steel, cement and fertilizers. Tunisian industries that export such products to the EU will either need to improve their energy efficiency and switch to cleaner energy sources, or face higher costs due to the CBAM. BESS integrated with solar PV and hybrid inverters could help Tunisian industries reduce their carbon footprint by optimising their energy usage. This will in turn lower their exposure to the CBAM and preserve their competitiveness in the EU market. The prospect of the CBAM provides therefore an additional market pull factor for Tunisian industries to explore battery storage solutions in the coming years. It creates an incentive for early action and investment before 2026 to avoid higher border tax exposure.

2.6 Management/Smoothing of load curve

Energy is consumed differently throughout the day and according to the season: there are peak and off-peak hours. A BESS system allows users to navigate between these periods, adjusting energy consumption and saving on electricity costs. Peak shaving is one of the most popular BESS use cases in load management. It involves reducing energy consumption during peak periods. At the same time, consumers can reduce their expenses, just as with energy arbitrage.

A battery storage solution can help to avoid peak loads on a power grid and therefore blackouts and other emergencies.

2.7 Black start

A BESS can help power plants and electricity grids to recover quickly from power outages. Instead of using a diesel generator, consumers can opt for a battery storage system, which is a cheaper and more environmentally friendly starting solution. A BESS can operate independently of the grid transmission line and provide power for as long as required, from a few minutes to several hours, when PCS is equipped with grid-forming inverter

2.8 Back-up power supply

BESS can provide power to homes, businesses, and other facilities, ensuring their continued operation. This is of vital importance to hospitals and other organisations that provide health, airport, and life safety services. Depending on the storage capacity, a BESS can provide backup power for as long as needed, even in the event of a serious grid failure.

2.9 Frequency and voltage control

Frequency and voltage can go out of their operating limits if the power supply is not synchronised with its actual demand. This can lead to power outages. A BESS can ensure the stability of a power grid or power system through voltage and frequency regulation. Due to its fast response time, a battery energy storage system becomes an effective grid balancing solution. As a first step, STEG will install a BESS within a total power of 200 MWh.

2.10 Transport and distribution

Transmission and distribution (T&D) lines are subject to ageing and depreciation due to peak loads and congestion. A battery storage solution can delay the upgrade of existing T&D lines and the construction of new infrastructure, reducing costs for the grid operator.

2.11 Introduction of STEP energy storage system and BESS

By 2050, new renewable energies will participate in Tunisia's energy mix in a massive way. By combining BESS with long duration technologies, Tunisia can optimize the utilization of its renewable energy resources. BESS can provide fast response times and short-duration energy storage, effectively managing fluctuations in renewable energy generation throughout the day. On the other hand, pumped storage systems can provide longer-duration energy storage, allowing for the management of energy imbalances over extended periods, such as overnight or during extended periods of low renewable energy generation, and especially in context of high penetration of renewables.

The main technology is that of pumped storage power stations (STEP). This system is linked to hydraulic energy and therefore to dams. Unlike a classic dam, it is based on the exploitation of two water reservoirs at different heights. When electricity production is abundant and inexpensive, and when it is surplus to the needs of the network, it is used to pump water from the lower basin to the upper basin. The upper basin thus becomes a storage place for energy that can be reused by gravity when needed. In this case, the water passes through a turbine that produces electricity.

This technology is used worldwide and allows large amounts of electrical energy to be stored using the potential energy of water. During peaks in consumption, STEG can bring their water retention dams into operation very quickly in about 6 minutes to meet the high demand.

The STEP can be activated as back-up power capacity. They consume more electricity than they produce and are activated as a last resort to secure the electricity grid. Depending on the capacity of the reservoirs and the type of machine, the production phase can last from a few hours to several days. As with all conventional hydroelectric power plants, the higher the waterfall between the two reservoirs the more powerful is the plant.

3 How can Tunisia introduce BESS: three policy actions

Based on the analysis of Tunisia's current energy sector, recent regulatory reforms, and the country’s strategic objectives for renewables, as well as on the technological overview and case studies, BESS can offer a promising opportunity to leverage the country's underutilized solar and wind resources, reduce dependence on fossil fuels, lower electricity production costs, and avoid the "duck curve" effect and curtailment losses. However, a coordinated action plan is needed to facilitate a smooth transition. We recommend focusing policy and regulations on three pillars:

Facilitating renewable energy integration

The deployment of BESS can help mitigate challenges associated with the intermittent nature of solar and wind energy. BESS can capture surplus renewable energy, inject stored power into the grid on demand, and smooth out fluctuations in supply. Regulations need to be revised to incentivize battery storage that can optimize solar output and provide grid services. In particular, changes could include:

- Establishing energy storage as a separate category of assets in future regulation, distinct from generation, transmission, and distribution value chains.
- Implementing a comprehensive regulatory framework that includes specific targets for energy storage in national energy policies. This framework should establish realistic goals and timelines to encourage the widespread adoption and deployment of BESS.
- Establish incentive mechanisms to promote investment in BESS while concurrently planning for the diversification of potential revenue streams as the technology improves in efficiency and confidence in these solutions grows.
- Implementing cross-sectoral legislation for energy storage in the existing RE schemes that outlines the ownership responsibilities of utilities, developers, operators, and regulators, and introducing a legislation for time-of-use tariffs (after the creation of an independent Regulatory Authority) would incentivize corporate power purchase agreements (PPAs) with storage.
- Increasing electricity selling price within Power Purchase Agreements (PPAs) with two price levels, the higher one for energy supplied during peak hours. Projects with storage should maintain competitiveness with STEG's prices: from 80 millimes to 270 millimes/kWh, including electricity transportation price. This would enable generating additional revenue in electricity transportation.
- Allowing a greater portion of renewable energy production to be sold in the self-consumption scheme from 30% to 50% of the total electricity generated. Continuing with the current regime could lead to the occurrence of losses due to the "duck curve" for some facilities.
- Eliminating the need for load shedding by enabling energy storage instead.

- A prudent step would be mandating a certain BESS capacity (e.g. 10%) in new power plants and industrial consumers over a threshold size. This will lay the groundwork for industries to gradually build experience with energy storage and identify viable use cases.
- Providing tax incentives, customs duty exemptions, accelerated depreciation and government equity ownership for battery storage technologies. This will encourage faster adoption by industries seeking to reduce energy costs and carbon emissions. The incentives can be gradually phased out as battery costs decline and the market matures.
- Supporting the inclusion of BESS as eligible assets in green financing frameworks.
- Conducting auctions for portfolios of renewable energy projects combined with energy storage assets to maximize the integration of renewable energy sources and to allow off-takers to purchase electricity that is fully dispatchable and offers enhanced stability.

For low voltage customers, transitioning from net metering to net billing and deploying smart meters will drive the uptake of hybrid inverter systems for distributed storage. These systems are aligned with STEG's vision. The net-metering scheme could be revised as the share of renewable energy in the power mix becomes substantial. The goal is to ensure that the scheme does not impede the integration of energy storage systems while still providing incentives for distributed renewable energy generation. This amendment should be designed to facilitate the integration of energy storage and maintain the incentives for adopting renewable energy at a local level.

Facilitating grid operations and management

BESS can increase efficiency, flexibility and reliability of energy systems, facilitating the duties of the grid operator. They can avoid costs associated with existing production subsidies, balance power demand and supply around the clock, improve process stability by smoothing fluctuations in voltage and frequency, store excess nighttime generation to offset daytime peaks. In this regard, encouraging the grid operator to invest in or, more efficiently and effectively, to procure services from stand-alone BESS (such as in the Italian case) from IPP by means of PPP would result in strengthening the power grid for a greater integration of variable and distributed energy resources and enabling the adoption of flexibility tools and demand response programs. Thus, it is crucial to learn from the experiences of other countries to ensure a successful project execution and acquire the necessary authorizations and permits for a project to be ready for construction.

Ensuring economic development and sustainability

In view of the introduction of the European Carbon Border Adjustment Mechanism (CBAM) for Tunisian exports to Europe, BESS offer a technically sound approach in line with the proposed policy. Imported goods to Europe should have at least 25% of the manufacturing energy derived from renewable sources, thereby a higher reliance on sustainable energy and batteries would go in the right direction, as carbon prices are projected to rise and stabilize around US$85 per tonne of CO_2 equivalent in the near term.

At the same time, should a production of batteries take place in Tunisia in the future, it would have to be aligned with the CBAM on sustainability credentials. Standards are therefore needed to identify allowed battery chemistries and technologies, as well as requirements for importation, transport, installation, use and end-of-life recycling. In this regard, it is important to:

- Monitor market developments to periodically update the regulatory framework for batteries: based on tech cost trends, supply issues, circular economy imperatives and wider energy transition goals. This will ensure Tunisia's battery regulations stay relevant and effective.
- Develop programs to raise awareness and build capacity: both for industrial consumers on the benefits of energy storage and for suppliers on market opportunities. This will catalyse the rapid growth of the nascent battery storage market in Tunisia.
- Set sustainability and safety standards for battery technologies: this includes rules around material sourcing, recycling, performance and durability. Such standards will boost confidence in battery solutions and promote responsible supply chains.
- The technical standards for the BESS system should be introduced in the tender documents and the environmental standards that will set the power limit should be determined as well as the costs for the concession scheme in the BESS PPA contract.
- The technical standards should be introduced in the renewable energy code that will be launched by 2024.

In details, certification as per the IEA 60086 international battery standard serves as tangible evidence that a battery product meets globally recognised performance criteria with respect to safety, quality and reliability. Accreditation per the aforementioned IEC battery specifications not only assures end users of the product's adherence to stringent technical parameters but also:

- Establishes industry credibility for the battery manufacturer, helping to build consumer confidence in their offerings
- Provides objective proof of the product's ability to perform as designed while maintaining electrical and mechanical safety
- Signals to buyers that the product meets interoperability requirements and is suitable for a wider array of applications, thus increasing marketability and potential revenue

Batteries that lack IEC 60086 marking should be prohibited from the market given that in the absence of third-party certification, end users have no concrete way to independently verify a battery product's essential attributes. Standards like IEC 60086 thus serve a vital role in promoting a culture of quality, consistency and safety within the battery industry and for energy technologies more broadly.

- Safety
    - UL-1642, 5th Edition: Standard for Lithium Batteries
    - UL-9540, 2nd Edition: ANSI/CAN/UL Standard for Energy Storage Systems and Equipment
- Testing

- UL-9540A, 4th Edition: ANSI/CAN/UL Standard for Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems
- UL-1973, 2nd Edition: ANSI/CAN/UL Standard for Batteries for Use in Stationary, Vehicle Auxiliary Power and Light Electric Rail (LER) Applications
- UL-1974, 1st Edition: ANSI/CAN/UL Standard for Evaluation for Repurposing Batteries

- JIS C 8715-2: Secondary Lithium Batteries for Use in Industrial Applications - Part 2: Tests and requirements of safety

Table 14: Standards to respect according to International Electrotechnical Commission, French and European norms[34]

Type of battery	Security	Performance	Transport
Lead batteries (Starter, stationary, general-purpose traction)	NF EN 50342, IEC 60896-X, IEC 61056-X, IEC 60254-X, IEC 61427-1		
Ni-Cd batteries	IEC 62133-1	IEC 61951-1, IEC 60623, IEC 60285, IEC 61959, BS EN 2570:1996 (Technical specification)	
Ni-MH Batteries	IEC 62133-1	IEC 61951-2	
Lithium Batteries	IEC 62133-2	IEC 61960, BS EN 60086-4:2000, IEC 60086-4:2000 UL 1642 (Safety of Lithium-Ion Batteries – Testing)	IEC 62281, UN38.3 ST/SG/AC.10/27/ (United Nations recommendations on the transport of dangerous goods)

Analysis of the environmental impact of recycling batteries

The current regulatory framework for batteries needs modernization to ensure the sustainability and competitiveness of battery value chains. This can be achieved by introducing mandatory sustainability requirements, including carbon footprint rules, minimum recycled content, performance, and durability criteria. Safety and labeling requirements for marketing and commissioning of batteries are also necessary. Additionally, implementing end-of-life management requirements and obtaining permits from the "Agence Nationale de Gestion de Déchets" (National Waste Management Agency) for storing used batteries in designated warehouses are essential steps.

To promote sustainable energy development, it is vital to focus on the research and development of grid-scale energy storage systems and introduce battery recycling incentives to properly collect,

[34] Directive and guidelines to be followed:2006/66/EC: Prohibition of the use of mercury, Marking Hg, C d, or Pb if threshold exceeded, Capacity (Ah or Wh), Recycling (separate collection), Recycling (ex: 65% of Pb batteries must be recycled). 2014/35/EU: LOW VOLTAGE DIRECTIVE. 2014/30/EU: ELECTROMAGNETIC COMPATIBILITY. CE marking: CE marking.

store, and transport waste lithium-ion batteries. Incorporating technical standards for BESS systems in tender documents and defining power limits and concession scheme costs in the BESS Power Purchase Agreement (PPA) contract will facilitate smoother implementation.

As battery storage technology rapidly evolve and become more widespread, new challenges will arise, especially in terms of insurance coverage. Insurers may struggle to keep up with the evolving technical aspects and risks associated with various battery technologies. Standardization and clear protocols for evaluating risks and losses are necessary to address these uncertainties.

Overall, updating the regulatory framework, promoting advanced energy storage technologies, and addressing insurance concerns will pave the way for sustainable and efficient battery storage implementation.

ANNEX - CASE STUDIES

1 The Italian Market

Battery energy storage system (BESS) capacity in Italy reached 587MW/1,227MWh in the first three months of 2022, of which 977MWh is distributed energy storage, according to the National Renewables Association (ANIE Rinnovabili). Terna expects 94,8 GWh of storage installed by 2030.[35]

In Italy, in fact, the BESS market is currently represented by residential and industrial segments, mainly combined with PV systems. ANIE's bulletin said that 97% of the distributed BESS units, which now stand at 95,869 in total, are combined with a solar PV system and 97% are residential. 98.2% are lithium-ion-based with lead-based, flywheel batteries and supercapacitors making up the rest. Some 95% of them are small size, less than 20 kWh.

The above number and impressive increase in the market were due to new incentive schemes for deploying residential and commercial storage systems alongside PV. Among the total amount of power installed in Italy, grid operator Terna owned 60MW/250MWh.

The number and capacity of utility-scale BESS projects operating in Italy will grow in the coming years with several large systems set to come online in 2023. The Italian Transmission System Operator (TSO), Terna, recently awarded 1.1GW of equivalent capacity contracts to energy storage assets for delivery in 2024.[36]

Specifically, in the large-scale BESS development, Terna played an important role through the capacity market mechanism. HV grid development and stability are considered strategic by Terna, which is in charge to strengthen and maintain the stability of the national grid, keeping in consideration the new renewables plants that will be installed in the future. In Italy, the TSO is in fact the owner of the key HV grid parameters that define which grid nodes are suitable for BESS installation or need expansion and define the development of the grid. For this reason, in 2019, such new "capacity market" was established, by which Terna procures capacity through futures contracts awarded through a competitive bidding process. Capacity market operation are defined in the Regulation and related annexes approved by Italian Ministerial Decree of 28 June 2019.[37]

The operators of the capacity selected as a result of the tender have the right to receive an annual fixed premium from Terna. This mechanism has attracted many operators who have invested in asset development and have started and obtained authorization process of the plants to be presented in the tender. For instance, the Capacity Market guarantees precisely those long-term price signals, anchored to resource availability, which the system needs in order to guarantee renewal and a better performance, also from environmental point of view, thus enabling a better adaptation to future needs of the system.

[35] See https://download.terna.it/terna/Documento_Descrizione_Scenari_2022_8da74044f6ee28d.pdf
[36] See https://www.energy-storage.news/capacity-market-contracts-awarded-to-more-than-2gw-of-battery-storage-in-uk-and-italy/.
[37] See https://www.terna.it/en/electric-system/capacity-market/regulations.

Typical permitting procedure in Italy[38]

Currently, according to Article 1, paragraphs 2-quater and 2-quinquies of Decree-Law no. 7/2022, introduced by Article 62 of Decree-Law no. 76/2020 and subsequently amended, the construction of electrochemical storage systems for the needs of the electricity sector, including energy conversion systems, grid connections, and any related and ancillary works, is authorized based on the following procedures:

a) BESS located within areas where any type of industrial plants are situated, including those that are no longer operational or undergoing decommissioning, or located within areas where electricity production plants powered by renewable or fossil fuel sources with a thermal power of less than 300 MW are in service, or located in quarrying areas or areas of production and treatment of liquid and gaseous hydrocarbons in the process of decommissioning, which do not involve the expansion of the areas, increased height compared to the existing situation, or require changes to adopted urban planning instruments, are authorized through the simplified municipal authorization procedure. If none of the above conditions are met, the procedure described in letter b) applies.
b) BESS located within areas already occupied by electricity production plants powered by fossil fuels with a thermal power of greater than or equal to 300 MW in service, as well as stand-alone plants located in non-industrial areas, and any grid connections, are authorized through a single authorization issued by the Ministry of Environment and Energy Security, in accordance with Article 12 of Legislative Decree of December 29, 2003, no. 387. In the case of plants located within areas where facilities for the production or treatment of liquid and gaseous hydrocarbons are present, authorization is granted in accordance with the applicable regulations.
c) BESS to be operated in combination with electricity production plants powered by renewable sources are considered connected works to the aforementioned plants, in accordance with the current regulations, and are authorized through:
    - A single authorization issued by the region or provinces, or, for plants with an installed thermal power exceeding 300 MW, by the Ministry of Environment and Energy Security, in accordance with the provisions of Article 12 of Legislative Decree of December 29, 2003, no. 387, if the renewable energy production plant is to be constructed.
    - Modification procedure according to Article 12, paragraph 3, of Legislative Decree of December 29, 2003, no. 387, following the provisions of the single authorization for substantial modifications to renewable energy plants if the renewable energy production plant is already constructed and the electrochemical storage system involves the occupation of new areas compared to the existing plant.
    - Simplified authorization procedure if the renewable energy production plant is in operation or authorized but not yet in operation.

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[38] See https://documenti.camera.it/leg19/dossier/pdf/AP0055.pdf#page=63&zoom=100,129,132.

d) The construction of electrochemical storage systems with a capacity below the threshold of 10 MW, regardless of their location, is considered a free activity and does not require the issuance of an enabling permit, subject to obtaining the necessary approvals in cases of cultural or landscape constraints, as well as opinions, authorizations, or clearances from the competent territorial authorities, as specified by specific provisions of the current legislation on environmental, safety, and fire prevention matters. Approval for connection by the national transmission system operator or the reference electricity distribution system operator is also required. The entities intending to construct such systems are required to send a copy of the relevant project to the national transmission system operator, who may provide comments within thirty days if a connection to the national electricity grid is requested. These comments should also be sent to the authorities responsible for issuing the authorizations, which must be communicated to the transmission system operator for monitoring the achievement of national energy storage objectives set forth in the Integrated National Plan for Energy and Climate.

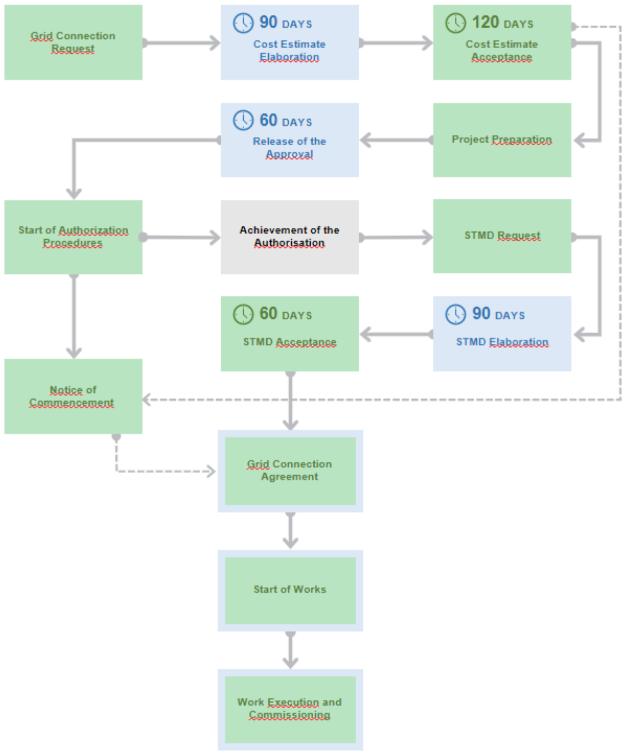
Stand-alone electrochemical storage systems and their grid connections are not subject to environmental impact assessment procedures or feasibility assessment, unless the connection works exceed some thresholds.

Grid Connection process

Another procedure to be followed is the Grid connection request to TERNA, through which Terna shares the design of the connection. First step is presenting STMG (or TICA, minimum general technical solution) and if the request is positive, further steps will follow according to the flow below.

Afterwards the project, endorsed by Terna, is included in the project of works subject to AU and presented to the competent Administration for authorization for construction and operation. The AU pursuant to Legislative Decree no. 387/03 makes possible to authorize all the RTN (National transmission grid) works necessary for connection at the same time as the production initiatives to which they are associated.

Figure 27: TERNA procedure flow chart

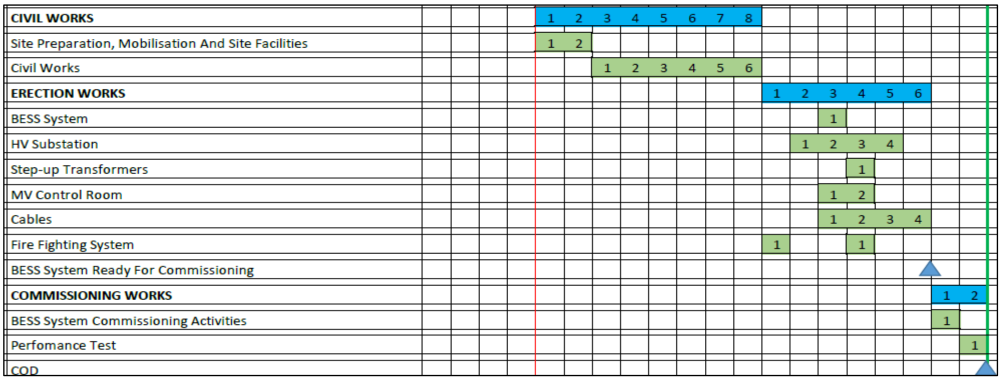


Technical configuration

Apart the storage system associated to PV plant in domestic application, majority of BESS of bigger size are destinated to capacity market or other ancillary services to the grid. It can be observed that the size of such standalone battery storage currently in construction is between 20-130 MW with capacity of 2 or 4 hours of energy storage. Typical single container size adopted is 3.5 MW. As average parameter for BESS sizing and land evaluation, based on current technology, it is considering 100 MWh/hectare.

The manufacturing process duration depends on BESS size. For instance, for big sizes (above 80 MW) the process can last 14-18 months up to site delivery. In the picture below a typical construction schedule for middle-big size plant is depicted, where each square represents a month.

Figure 28: Typical construction schedule



2 The UK Market

This section covers the fundamental steps that solar and storage projects developed in the UK must go through in order to obtain the required authorizations and to reach the Ready-to-Build stage (RtB). The two main process of authorization are covered:

- Grid connection process
- Planning process

Grid Connection process

The Transmission System Operator (TSO) for Great Britain is National Grid Electricity System Operator (NGESO) while for Northern Ireland is System Operator for Northern Ireland (SONI). Furthermore, there are six Distribution Network Operators (DNOs) covering specific regions of Great Britain, plus one covering Northern Ireland:

- Scottish and Southern Electricity Networks (SSEN)
- Scottish Power Energy Networks (SPEN)
- Northern Powergrid (NP)
- Electricity North West (ENW)
- National Grid Electricity Distribution (NGED)
- UK Power Networks (UKPN)
- Northern Ireland Electricity Networks (NIEN)

The process of interconnection to the electricity grid can take different paths according to:

- Location of the project (England, Wales or Scotland);
- Connection voltage level (Distribution or Transmission network) and
- Size of the project (30 MW 50 MW 100 MW being key thresholds).

According to the combination of the above parameters a project can require one of the following agreements:

- Grid Connection Agreement (GCA);
- Bilateral Connection Agreement (BCA);
- Bilateral Embedded Generation Agreement (BEGA);
- Bilateral Embedded Licence Exemptible Large Power Station Agreement (BELLA).

If a project is connected to the Distribution network and is classified as "small". it only requires a GCA with a DNO. If a project is connected directly to the National Electricity Transmission System (NETS), a BCA is required. If a project connected to a DNO is classified as "medium" or "large", a BEGA is required. In this case, despite the system not being connected directly to Transmission Network it impacts it indirectly due to its size and requires the NGESO to be notified. For example. If a project is more than 50 MW in size and it is located in England or Wales, it requires a BEGA, if it is up to 49.9 MW it doesn't require a BEGA.

In special case of plants located in Scotland, if a project is under 100 MW but is labelled as "large", it is subjected to a BELLA. Customers with a BEGA or BELLA can export onto the NEST and participate in the energy balancing market, called Balancing Mechanism (BM).

The general overall scope of BCA, BEGA and BELLA agreements is to state the requirements and provisions that the customer needs to satisfy to comply with the relevant codes:

- Connection and Use of System Code (CUSC);
- Grid Code; and
- Balancing & Settlement Code (BSC).

Table 15: Types of Grid Connection Agreements

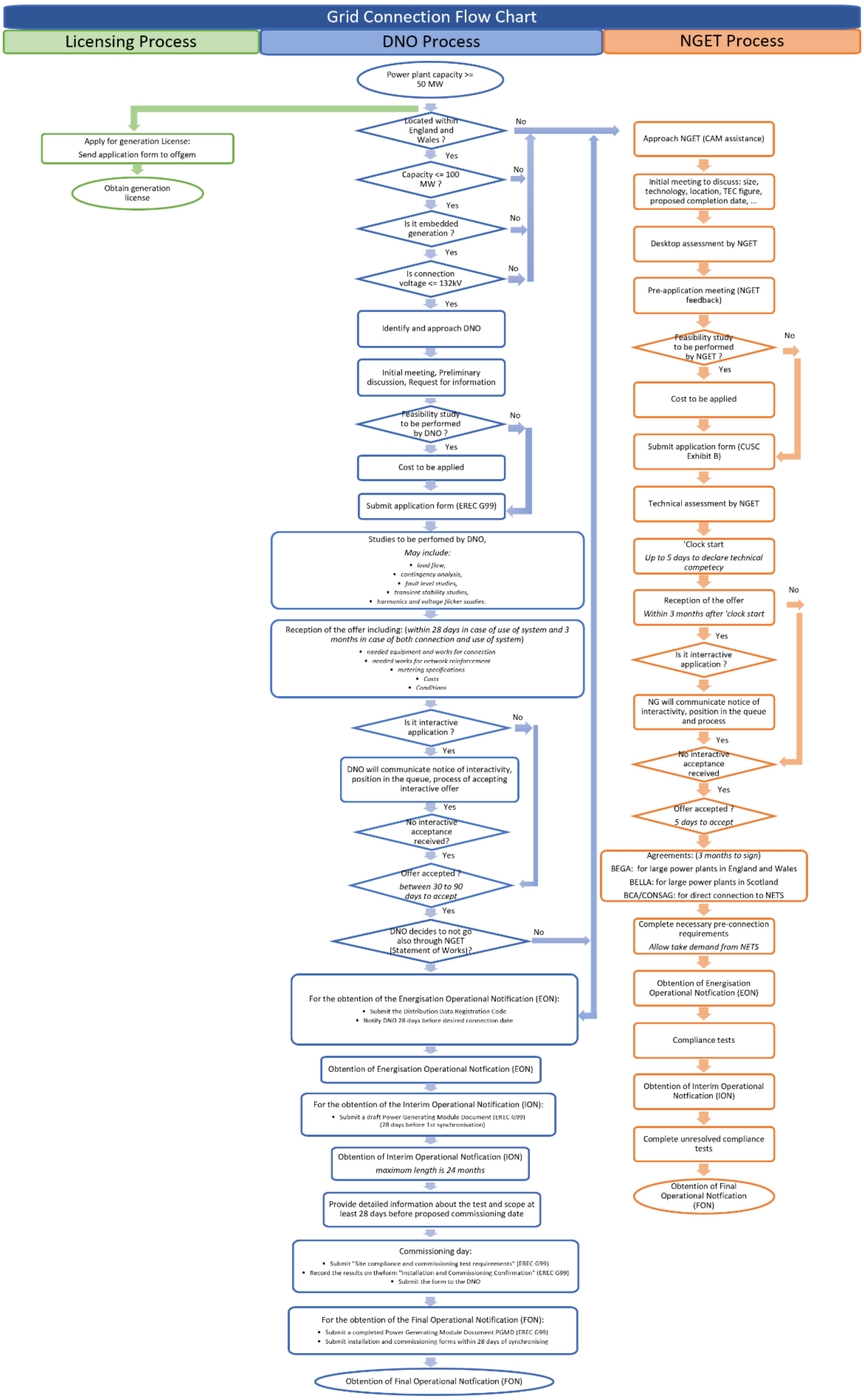
Agreement type	Applicability
Bilateral Connection Agreement (BCA)	Users Directly Connected to the NETS
Bilateral Embedded Generator Agreement (BEGA)	Users Connected to DNO Networks
Bilateral Embedded Licence Exemptible Large Power Station Agreement (BELLA)	Large users under 100 MW

Table 16: Transmission Operators in different areas of the UK and labelling of plant sizes.

TO and area	Small	Medium	Large
NGET in England and Wales	<50 MW	50-99 MW (requires BEGA)	≥100 MW (requires BEGA)
SPT in Southern Scotland	<30 MW	Not applicable	≥30 MW (requires BELLA)
SHETL in Northern Scotland	<10 MW	Not applicable	≥10 MW (requires BELLA)

A more detailed overview of the Grid Connection process is presented in the flowchart in Figure 29, which encompasses a variety of scenarios highlighting the steps in which an interaction with DNOs and or NG is required. More detailed information is available on the NGESO website.

Figure 29: Grid Connection Flowchart



Planning process

The UK planning process is designed to ensure that all potential impacts of a proposed development and associated impact mitigation are considered by appropriate statutory and non-statutory consultees under a single permitting process. While this provides a more streamlined approach to permitting than in many countries, BESS and ground mounted solar developers are advised to engage a qualified and experienced agent to provide, submit and follow up on a planning application of this type. An appropriately selected agent will have a network of trusted independent sub-consultants to undertake the required surveys and reports, have a comprehensive understanding of the details and potential hurdles of the planning process, particularly in relation to solar and BESS projects, and have extensive experience in engaging with planning officers, statutory consultees and local communities.

The planning application is affected by a number of parameters, the most significant being:

- The location of the project (England and Wales, Scotland or Northern Ireland)
- The size of the plant (large plants will be categorized as Nationally Significant Infrastructure Project (NSIP))
- Its environmental impact (large plants usually require an Environmental Impact Assessment (EIA))

Depending on the location, the permitting process is governed by different body of legislation:

- Town and Country National Planning Act 1990 (for England and Wales),
- Town and Country National Planning (Scotland) Act 1997 and
- Planning Act (Northern Ireland) 2011.

Depending on its size, a project could fall under different categories:

- < 50 MW, planning applications are submitted to and decided by the Local Planning Authority (LPA)
- > 50 MW, the project will be categorized as Nationally Significant Infrastructure Project (NSIP), and the permitting process falls under the jurisdiction of the Planning Inspectorate (central government body, rather than local council). Since July 2020, this categorization doesn't apply to BESS projects, that can be equally authorized by LPAs even if larger than 50 MW.

Depending on the environmental impact that the project, a project could be:

- Required to provide a EIA, when the project is likely to rise in terms of environmental effects, due to its size or location in a particularly environmentally sensitive or vulnerable areas; or
- Otherwise, not required to provide a EIA

Prior to submitting a planning application, a pre-planning application is submitted to initiate the discussion with the LPA, and this consist of requesting the LPA for a EIA screening decision regarding whether a EIA is required, and a pre-application advice from the LPA in order to improve the quality of the planning application and the likelihood of success. More detailed information is available on the government website,[39] and an overview of the iterative steps following a Planning application and its eventual amendments are pictured in Figure 30.

Figure 30: Flowchart of permitting process in the UK[40]

[39] See https://www.gov.uk/government/publications/plain-english-guide-to-the-planning-system/plain-english-guide-to-the-planning-system.
[40] See https://www.planningportal.co.uk/planning/planning-applications/the-decision-making-process/introduction.

UK BESS Revenue Streams

The UK BESS market provides six major revenue streams for the remuneration of grid services provide by BESS to the distribution and/or transmission electricity network:

- Balancing mechanism (BM)
- Capacity Market (CM)
- Firm Frequency Response (FFR)
- Enhanced Frequency Response (EFR)
- Dynamic Containment / Moderation / Regulation (DC/DM/DR)
- Wholesale market

Balancing Mechanism (Bm)

When electricity generation and consumption are not in balance, National Grid uses the balancing mechanism to purchase changes in generation and consumption to correct the mismatch. The balancing mechanism is an ad-hoc market with no forwards commitments and highly dynamic prices. Without an agreement with National Grid, such as a Bilateral Embedded Generation Agreement (BEGA), distribution connected assets cannot access the BM other than through a Virtual Lead Party (VLP). The VLP role is often performed by the Off-taker.

Capacity Market (Cm)

The capacity market was introduced in 2014 as part of the Electricity Market Reform and aims to ensure there is sufficient capacity during times of network stress. National Grid pays monthly £/MW payments to participants who make capacity available, this is known as an availability payment. When required due to an increased demand, National Grid issues a capacity market notice to participants and if a stress event looks likely, participants will be instructed to respond. Participants are paid a £/MW rate for response know as utilisation payments.

There are two capacity market auctions each year: T4 and T1. T4 is the main auction and buys most of the capacity needed for delivery in four years' time. In this auction, new build generators can secure 15-year agreements. T1 auctions are top up actions held just ahead of the delivery year to secure capacity that has fallen through since the T4 auction. Participants will bid an availability price and a utilisation price, and all participants are paid at the rate the market clears.

Firm Frequency Response (FFR)

Firm Frequency Response (FFR) is an ancillary service that has been designed to maintain the frequency of the grid by commissioning generations and consumers to alter their MW output in response to frequency deviations. For a BESS system it means charging when frequency is > 50HZ and discharging (acting like a generator) when frequency< 50Hz.

Static FFR is triggered when grid frequency drops below a specific threshold (49.7Hz). Dynamic FFR is where continuous rapid response is delivered for all frequency variations within the normal grid operating range of 49.5 to 50.5 Hz, to help keep the electricity system within a target frequency.

FFR is procured through a monthly tender. Once service providers succeed in the prequalification assessment and sign onto a framework agreement, they can participate in the tender process. Participants can tender for a single or multiple months. Having considered the quality, quantity and the nature of the services, National Grid will accept the most economical tender. This then becomes contractually binding.

FFR has a multi part payment structure, however, most participants only tender for availability fee (the number of hours of availability from a provider(£/h)) and Nomination fee (for each hour utilised (£/h)). Tenders alternate between short-term (month ahead only) and long-term (from month ahead to 30 months out). The maximum contract award is 24 months and the tender must start within 6 months of the first available tender date. FFR services are being slowly replaced by faster reacting Dynamic Response Service described below.

Enhanced Frequency Response (EFR)

Enhanced Frequency Response (EFR) is a similar service than FFR, but with the difference of intervention speed. The EFR requires a full response within half a second, which is at least 4x faster than FFR. EFR has been discontinued and has been replaced by the new suite of Dynamic Response Services described below. Existing EFR contracts will continue to

Dynamic Containment / Moderation / Regulation (DC/DM/DR)

Dynamic Containment (DC), Dynamic Moderation (DM) and Dynamic Regulation (DR) make up a new suite of Dynamic Response Services that NG uses to keep the network frequency at 50 Hz plus/minus 1%. DM and DR are pre-fault services, with DM being a fast-acting response and DR a slower acting response, while DC is a post-fault service. The response time for this suite of services varies between 0.5 and 2 seconds and lasts between 15 and 60 minutes. BESSs are well suited systems to deliver such service as batteries can intervene by charge or discharging in less than a second (millisecond range), and can represent a valid alternative to gas power generators.

These services are procured by NG in 24-hour blocks on a day-ahead basis, and the remuneration of is based on bids for each Electricity Forward Agreement (EFA) period and is paid as £/MW/h. If an asset breaches the market participation guidelines and agreements it incurs in penalties.

Wholesale market

The participation to wholesale market is slightly different depending if the BESS asset is Balancing Mechanism-registered (a Balancing Mechanism Unit, or BMU), or not (a non-BMU). BMU assets submit a physical notification to ELEXON, on a settlement period basis.
Wholesale arbitrage is profitable when the energy market price incurs in a substantial spread (for example £50/MWh wholesale spread). The energy market price is based on day-ahead hourly prices that allows asset optimizer to establish the best operational strategy for the BESS, especially if in combination with other services

.

3 Lessons Learned

By looking at the BESS market evolution in countries which are at a mature stage in terms of BESS adoption within the energy market, a number of lessons can be learnt and applied to early-stage markets such as in Tunisian case. In particular, in the previous sections we looked at two examples which are a different level of maturity: Italy and the UK. The Italian BESS market approached adoption of BESS systems only in the recent years, with no BESS capacity yet installed to provide services for the grid, but with legislation and policies being shaped to accommodate these new systems. The UK BESS market, instead, is at a more mature level, with 2 GW of BESS capacity installed to Q1 2023, and more defined revenue streams for BESS assets.

The first common trend that can be observed in both markets is the exponential growth of BESS project pipeline forecasted for the years ahead. Italy is forecasted to increase its BESS installed capacity from 587 MW (2022) to 1.1 GW (2024), and the UK is forecasted to increase from 2 GW (2023) to 6.5 GW (2025). On the longer term, the number of projects that have been granted grid connection in the UK exceeds 16 GW, and these projects are expected to be able to connect to the grid over the next decade (2023-2033), pending grid infrastructure reinforcements and upgrades.

A second interesting similarity between the case of Italy and the UK is the permitting process. Both countries present very similar high-level steps for a BESS project to reach the ready-to-build stage. These include the assessment of the environmental impact, the authorization from the local governmental authority, and the agreement with the network operator for the energy provision. Other technical aspects of project development can also be learned from advanced BESS markets such as the construction times, the project lifetime, the footprint area, the redundancy aspects, the type of connection to the grid (distribution or transmission), the co-location strategies with other renewable assets, etc.

Lastly, but most importantly, it is worth noting the different portfolios of revenue streams that the two markets are offering to BESS owners. Italy offers only three revenue streams to date (Capacity Market, Frequency Regulation, and Energy Market), while the UK offers a wider choice of revenue streams that BESS can tap into. Two main conclusions can be made. Revenue streams come into effect on a staged basis, following the order of priority dictated by the needs of the electricity network. Secondly, it is fair to assume that an increase in deployment of BESS projects (such as in the UK compared to Italy) will naturally lead to the creation of multiple and diverse revenue streams after the stakeholders have gained confidence in the potentiality of BESS solutions.

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