Electrical Grid Considerations and Development for SMRs

Qun (Annie) YU

NENP_NPES

YU, Qun (Annie)

- Over 28 years experience in nuclear power, across three Nuclear Power Plants and two International Organizations
- The first female Senior Advisor in Performance Analysis Central Team at World Association of Nuclear Operators (WANO)
- The first Chinese Senior Professional (P5 level) at the Department of Nuclear Energy at the IAEA
- Technical Lead on Management of Construction and Operation of Nuclear Power Plants
- Bachelor's degree in Electrical Engineering/ Master's degree in Nuclear Engineering

CONTENTS

- WHY ELECTRICAL GRID IS SO IMPORTANT FOR NPPS, INCLUDING SMRS?
- WHAT KIND OF ELECTRICAL GRID IS GOOD FOR NPPS?
- HOW TO DEVELOP THE ELECTRICAL GRID FOR NPPS?
- EARLY EXPERIENCE ON SMRS_GRID INTERFACE
- CHALLENGES FOR THE "OFF-GRID" SMRS DEPLOYMENT
- SPECIFIC CONSIDERATIONS FOR SMR COGERNATION
- HOW IAEA SUPPORTS MEMBER STATES?

WHY ELECTRICAL GRID IS SO IMPORTANT FOR NPPS, INCLUDING SMRS ?

- The electrical power systems (EPS) provide reliable power to all electrical auxiliary loads and transfer the electricity generated by the NPP to the electrical grid. EPS is needed during all modes of operation of NPPs: Startup, Normal operation and Reactor Shutdown.
- For most of operating NPPs, the EPS in NPP are needed for major safety functions: control of reactivity, transport of heat from the core and confinement of radioactive materials.
- **Electrical Grid is served as the offsite power supply in the Electrical Power Systems in the NPPs.**

WHY ELECTRICAL GRID IS SO IMPORTANT FOR NPPS, INCLUDING SMRS ?

- For existing large nuclear reactors, the availability of off-site (electrical grid) and on-site power supply is crucial as their safety systems mostly rely on active systems which need electrical power to operate.
- Although reliance on active systems for safety functions has been greatly reduced in SMRs designs, and no requirement for the provision of Alternating Current (AC) electrical power supplies to facilitate the actuation of safety functions. However, AC power supplies are needed:
  - *For maintaining the plant in a long term controlled state following an accident condition, including recharging the DC system if batteries operated beyond the defined operating time.*
  - *For recovery from an operational event which does not require actuation of passive safety features.*
- Offsite power remains essential for SMRs, but its role has **shifted from immediate safety dependency to operational and recovery support. Electrical Grid should always be considered as the preferred power supply, for NPPs, including SMRs.**

WHAT KIND OF ELECTRICAL GRID IS GOOD FOR NPPS?

- **Stable**
  - Frequency **(+/−1%)**
  - Voltage **(+/−5%)**
- **Reliable**
  - Events that disconnect parts of the grid, or lead to blackout of a major part of the grid are rare **(much less than once per year).**
  - The grid recovery following a regional blackout restores power for essential services, including offsite power for NPPs, in **less than two hours.**
- **Resilient**
  - The ability to limit the extent, severity, and duration of system degradation following an **extreme** event.

WHAT KIND OF ELECTRICAL GRID IS GOOD FOR NPPS?

Comparison of off-site power supplies (Electrical Grid) for large NPPs and SMRs.

	Large NPPs	SMRs
Off-Site Power Supplies	Two physically independent off-site power supplies.	A single off-site power supply might be acceptable for SMRs employing passive engineered safety features, according to a graded approach.
Transmission Lines	Two transmission lines for each off-site power supply.	A single transmission line for each off-site power supply may be acceptable if the safety analysis report shows that this arrangement achieves the technical safety objectives.

HOW TO DEVELOP THE ELECTRICAL GRID FOR NPPS?

- **Phase 1: Assessment**
  - The capabilities of the existing grid in relation to the SMR technology being considered, including its ability to reliably take a SMR base load output, its ability to withstand a loss of the plant's output and its ability to reliably supply off-site power during outages and in an emergency;
- **Phase 2: Enhancement**
  - All the plans for enhancing the electrical grid to meet the needs of connecting SMRs are in place, including funding.
- **Phase 3: Execution**
  - Ensure the completion of all upgrades and enhancements to the grid and interconnections;
- NG-T-3.2 Evaluation of the Status of National Nuclear Infrastructure Development (Rev.2)

KEY MEASURES TO ENHANCE THE RELIABILITY OF ELECTRICAL GRID

1. Strengthening Grid Infrastructures
   – Reinforced Transmission Lines
   – Redundant Systems
   – Decentralized Energy Resources
2. Regional and International Collaboration
   – Interconnected Grids
   – Cross-Border Agreements
3. Building Energy Storage Systems
4. Grid Modernization and Smart Technologies

CANADA_EARLY EXPERIENCE ON GRID_SMR INTERFACE

2021, Ontario Power Generation selected BWRX-300 SMR (300MWe) for the Darlington New Nuclear Project (DNNP).

•**Load Following**: The BWRX-300 can maneuver from 100% and 50% power, with a ramp rate of +0.5%/minute, and return to full power with the same ramp rate, daily.
•**Islanding**: The BWRX-300 can operate connected to the grid or can be operated independently with additional transformers and electrical protection relays.
•**Black Start:** Black Start capabilities are not included in the standard BWRX-300, but the BWRX-300 can start up from a completely de-energized state without receiving energy from the grid if equipped with additional equipment.

The DNNP SMR:

- To pursue two transmission line connections
- A baseload plant with no black start or load following characteristics
- Safety systems do not require AC power to function

CHINA_EARLY EXPERIENCE ON GRID_SMR INTERFACE

HTR-PM Demonstration Project

- First Grid Connection in 2021
- **Core Damage Frequency (CDF): 0**
- Passive safety features
- Base load Operation
- Capable of operating in islanding mode

HTR-PM Cogeneration Projects

- 4 HPR1000 units and 2 sets of HTR-PM600
- First Concrete Date in 2026
- Industrial heating + Electricity Generation

- ❖ Electrical power systems in HTR-PM are similar to the conventional reactors, but the no emergency diesel generators for safety functions.
- ❖ Two off-site power supply sources + two transmission lines for each off-site power

CHINA_EARLY EXPERIENCE ON GRID_SMR INTERFACE

ACP100

- First Concrete Date in 2021,
- First Grid Connection expected in 2026
- Rated capacity：128.35MW
- Passive Safety Features
- Capable of operating in islanding mode

❖ Base load Operation

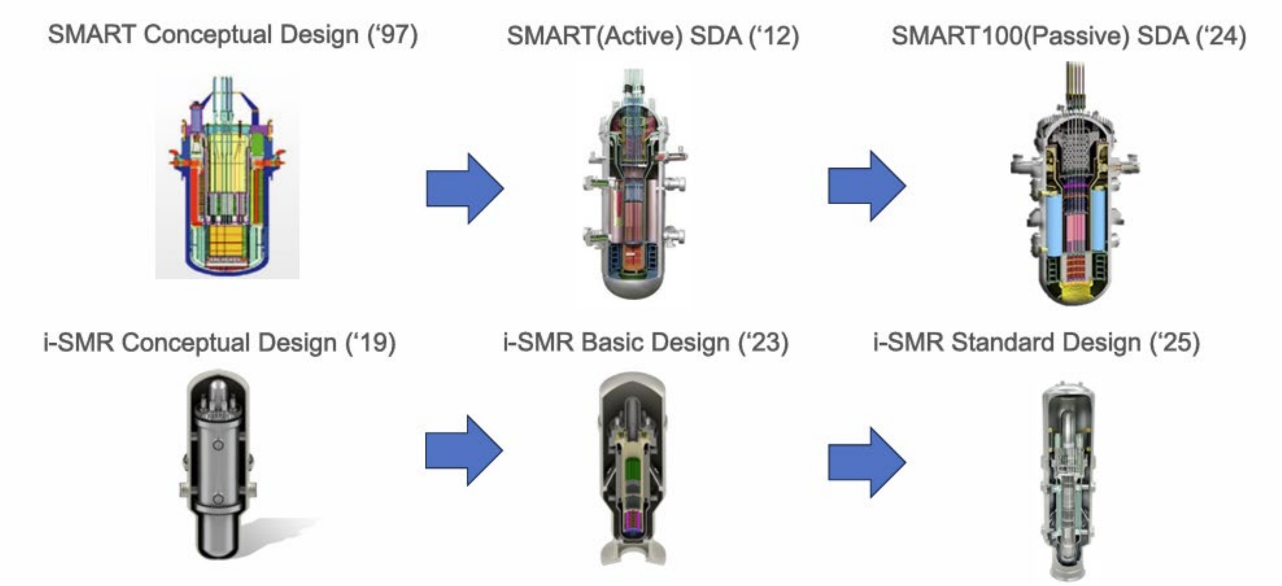
❖ Similar Electrical power systems design to the conventional reactors

❖ No emergency diesel generators for safety functions.

❖ Two off-site power supply sources + two transmission lines for each off-site power supply

KOREA_EARLY EXPERIENCE ON GRID_SMR INTERFACE

SMART 100
- Nuclear Regulator approved in 2024
- Electrical output: 100-110 MW
- Passive safety features



iSMR
- Initiated in 2020
- Basic Design completed in 2023
- Expected to be approved in 2028
- Electrical output: 170 MW
- Passive safety features

❖ With Black Start & Load following characteristic

❖ Although exempt from the requirement of two physically independent off-site power sources, it is designed with two electrically independent off-site power sources to enhance the availability of offsite power.

USA_EARLY EXPERIENCE ON GRID_SMR INTERFACE

NuScale US 600

- NRC approved in 2000
- 12 modules X 50 MW=600 MW
- Passive safety features
- No reliance on AC power for safety functions
- Offsite power system includes one or more connections to a transmission grid, micro-grid, or both.
- Capable of operating in islanding mode

NuScale US 460

- Submitted to NRC for approval in 2022
- 6 modules X 77 MW=462MW
- Passive safety features
- No reliance on AC power for safety functions
- Offsite power system includes one or more connections to a transmission grid, micro-grid, or dedicated service load.
- Capable of operating in islanding mode

CHALLENGES FOR THE “OFF-GRID” SMRS DEPLOYMENT

Feature	Grid-Connected SMR	Remote/Off-Grid SMR
Primary OSP source	Large transmission grid	Often none
Redundancy method	Multiple grid circuits	Multiple on-site generators
Short-circuit strength	Provided by grid	Must be engineered locally
Black-start	Grid-supported	Fully self-contained
Frequency stability	Grid provides inertia	Must provide internally
Recovery after SBO	Grid restoratio[illegible]ely	May require on-site resources only

CHALLENGES FOR THE "OFF-GRID" SMRS DEPLOYMENT

🧩 SMRs in remote grids often operate under:
🔻 Low inertia
👥 Few generators
📉 Limited reserves
➡️ SMR may supply a large share of total generation
⚠️ What happens?
Low inertia + Large unit size
⬇️
Very fast frequency changes
⬇️
High risk of instability or blackout
🎯 Core Challenge:
Maintain stable frequency without support from a large grid

🛠️ Engineering Strategies
1. System Design
- 🚫 Avoid single large unit dominance
- 🔗 Use multi-module SMRs

2. Generation Mix
- ⚙️ Add hybrid sources (diesel • gas • renewables)

3. Grid Support
- 🔋 Include fast-response systems *(optional to add if needed)*

4. Resilience
- 🔄 Ensure black-start capability

SPECIFIC CONSIDERATIONS FOR SMR COGENERATION

Phase 1

- The size of the reactor and the anticipated demand for heat and other product(s).
- The load profile for heat or other demand for non-electric products during expected operation and over the lifetime of both nuclear and user facilities. Is there a possibility that the user facility will be decommissioned before the reactor(s) are decommissioned?
- Whether the nuclear facility will be connected to the grid or dedicated solely to the user facility.
- Provisions for black-start capability and islanding operation needs be included if the nuclear facility is proposed to connect to a microgrid or to operate as a stand-alone facility.
- The load-following capability of the grid system across different seasons, and the requirements imposed on the nuclear project.
- How the grid responds to a large load drop or increase (from trips of the NPP caused by the user facility, especially in the case of large facilities such as large-scale hydrogen electrolysers).

SPECIFIC CONSIDERATIONS FOR SMR COGENERATION

Phase 2

- Analysis of the impact on the grid under various scenarios combining electric and non-electric generation, with particular emphasis on mode transitions and their dynamic impact on the grid, such as transitioning from cogeneration to stand-alone electrical operation.
- Adequate design of generators and unit transformers, taking into account the characteristics and lifespan of non-electric production.
- The possible installation of batteries or thermal storage needs to be evaluated, considering load-following requirements and cross-market interactions.
- Redundant transmission capacity for off-site power has to be ensured, which is sufficient to address both the safety needs of the reactor and the requirements of the user facility (facilities). Off-grid configurations may require additional capacity for off-site power.
- Backup systems that may be required for the continuous supply of electricity and of heat to the industrial process.

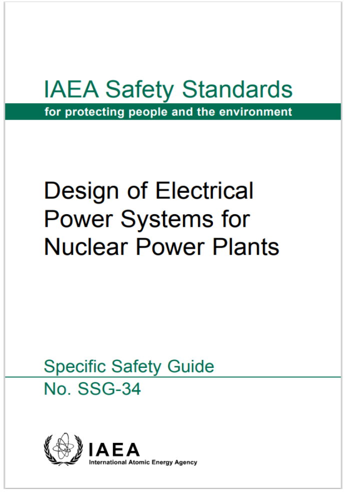
SPECIFIC CONSIDERATIONS FOR SMR COGENERATION

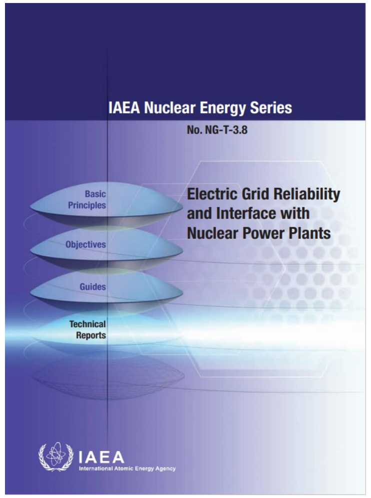
Phase 3

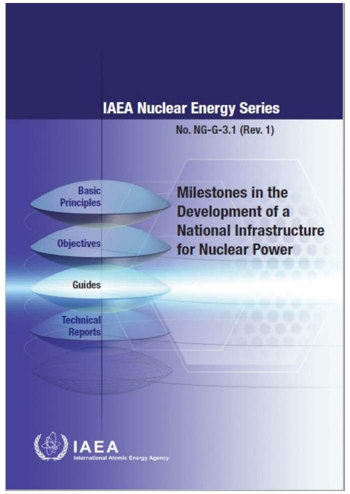
- O/Os and Grid Operator – Make operational arrangements to ensure coordination between electric and supply for non-electric products. These would include, but not be limited to, generation plans, maintenance plans, and contingency plans.
- O/Os and Grid Operator – Continuously analyse the impact on the grid and select appropriate protection settings to ensure coordination between the grid, the NPP, and other production beyond electricity.

HOW IAEA SUPPORTS MEMBER STATES IN THE AREA?

- IAEA Milestones Approach (INIR)
- Technical Cooperation Activities
  - Trainings/Workshops
  - Expert Missions
  - Scientific Visits
- Publications
- Conferences/Meetings







HOW IAEA SUPPORTS MEMBER STATES IN THE AREA?

1. Training/Workshops

❖ Phase 1: To provide information, guidance and practical experience on NPP integration into the grid;

- Good engineering practices and power studies when connecting NPP to the grid
- Compliance between grid performance standards and NPP safety and technical requirements
- Evaluation of electrical grid reliability;
- Grid reliability and resilience for and with NPP safe operation.

❖ Phase 2/3: To provide deep-diving training/workshops on some specific topics which the MS has strong interests.

HOW IAEA SUPPORTS MEMBER STATES IN THE AREA?

2. Expert Missions

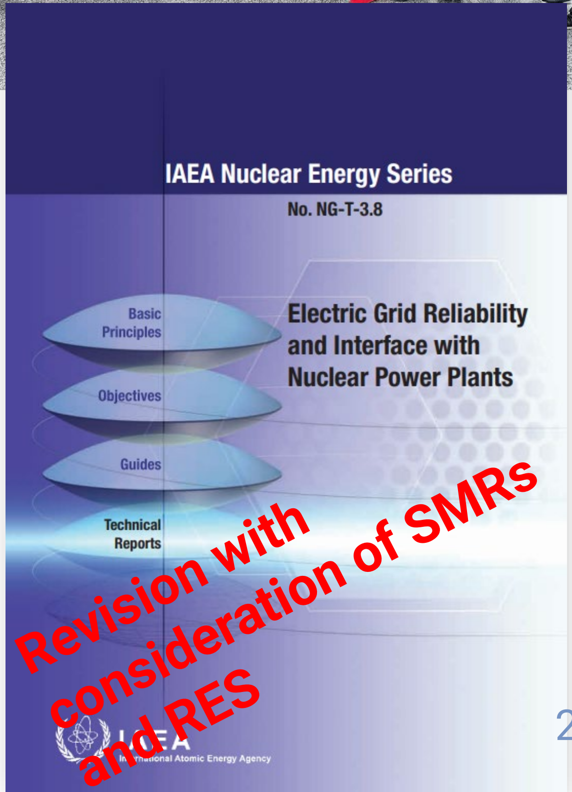
- ❖ Phase 1: To provide guidance on how to perform technical studies on NPP connecting to the electrical grid.
- ❖ Phase 2/3: To provide the independent expert insights to review the results of technical studies on NPP connection to electrical grid.
- ❖ To provide expert support for some specific issues in the areas.

3. Scientific Visits (Phase 1/2/3)

- ❖ To arrange Scientific Visits to the operating countries to gain the hands-on experiences and discuss the technical issues with first-line mangers and engineers on electrical grid interaction with the NPP.

ELECTRIC GRID RELIABILITY AND INTERFACE WITH NUCLEAR POWER PLANTS, NG-T-3.8 …under Revision!

- New draft prepared and reviewed by MS
- Specificity of Small Modular Reactors added and interface with Renewable Energy Sources
  - Design features of EPS of SMRs
  - Interaction of the grid system with Renewable Energy Sources
  - Early experiences regarding SMRs and electrical grid connection

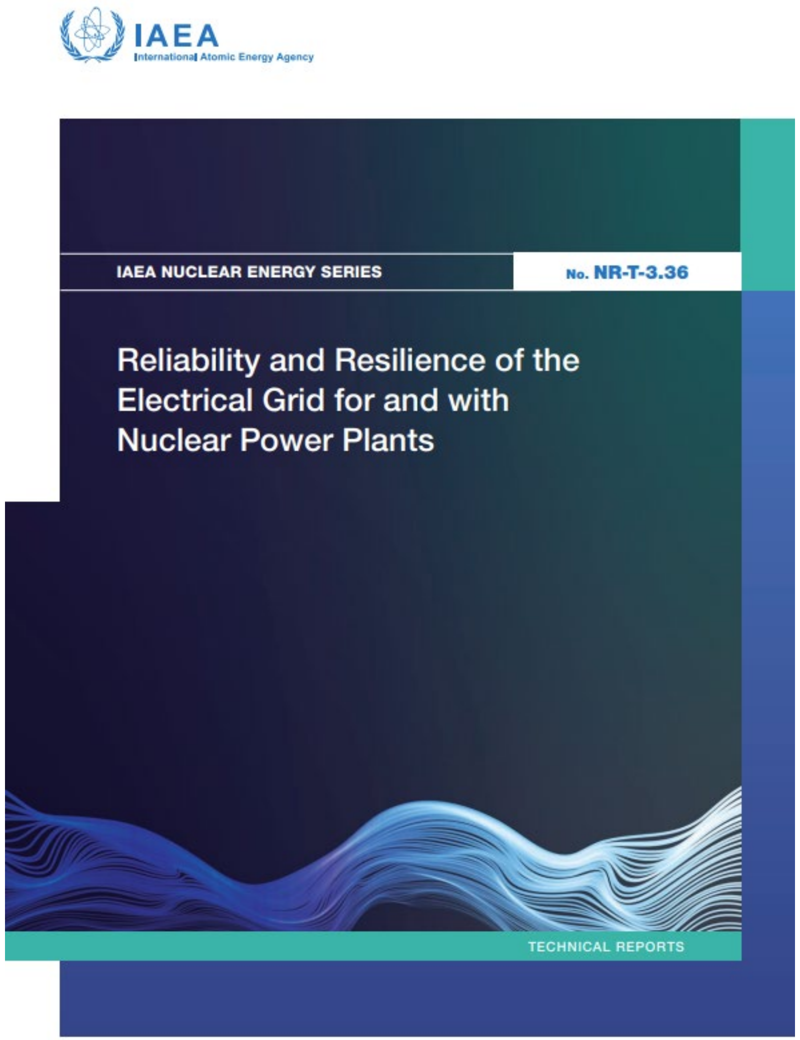


New Publication: RELIABILITY AND RESILIENCE OF ELECTRICAL GRID FOR AND WITH NUCLEAR POWER PLANTS (NR-T-3.36)

This publication reviews requirements regarding the key areas of interfacing and operating electrical grids with Nuclear Power Plants (NPPs). Challenges and potential solutions are detailed.

This guidance is particularly focussed on assisting Member States in establishing and sustaining a reliable and resilient electrical grid in support of the safe and efficient operation of NPPs, and the contributions of NPPs to enhancing the reliability and resilience of the grid system.

Download Link: Official Version



LINKS TO THE RELATED PUBLICATIONS

IAEA Safety Standards Series

1. Fundamental Safety Principles, IAEA Safety Standards Series, No. SF-1,2006
2. Safety of Nuclear Power Plants: Design, IAEA Safety Standards Series, No. SSR-2/1 Rev.1, 2016
3. Safety of Nuclear Power Plants: Commissioning and Operation, IAEA Safety Standards Series, No. SSR-2/2 Rev. 1, 2016
4. Design of Electrical Power Systems at NPPs, IAEA Safety Standards Series, No. SSG-34, 2016
5. Establishing the Safety Infrastructure for a Nuclear Power Programme, No. SSG-16, 2020

IAEA Nuclear Energy Series

1. Power Uprate in Nuclear Power Plants: Guidelines and Experience, IAEA Nuclear Energy Series, No. NP-T-3.9,2011
2. Electric Grid Reliability and Interface with Nuclear Power Plants, IAEA Nuclear Energy Series, No. NG-T-3.8, 2012
3. Milestones in the Development of a National Infrastructure for Nuclear Power, IAEA Nuclear Energy Series, No.NG-G-3.1 Rev.1, 2015
4. Evaluation of the Status of National Nuclear Infrastructure Development IAEA Nuclear Energy Series, No.NG-T-3.2 Rev.1, 2016
5. Non-baseload Operation in Nuclear Power Plants: Load Following and Frequency Control Modes of Flexible Operation, IAEA Nuclear Energy Series, No. NP-T-3.23, 2018
6. Reliability and Resilience of Electrical Grid for and with Nuclear Power Plants (NR-T-3.36)

LINKS TO THE RELATED PUBLICATIONS

IAEA Technical Reports and Others

1. Interaction of Grid Characteristics with Design and Performance of Nuclear Power Plants: A Guidebook. IAEA Technical Reports Series No. 224, 1983
2. Introducing Nuclear Power Plants into Electrical Power Systems of Limited Capacity, IAEA Technical Reports Series No. 271, 1987
3. Enhanced Electricity System Analysis or Decision Making — A Reference Book, Decades Project Document, No. 4, 2000
4. Design Provisions for Withstanding Station Blackout at Nuclear Power Plants, IAEA-TECDOC-1770,2015
5. The IAEA Director General's Report on the Fukushima Daiichi Accident, September 2015
6. Impact of Open Phase Conditions on Electrical Power Systems of Nuclear Power Plants, IAEA Safety Reports Series, No.SRS-91, 2016
7. Design Safety Considerations for Water Cooled Small Modular Reactors Incorporating Lessons Learned from the Fukushima Daiichi Accident, IAEA-TECDOC-1785, 2016

KEY TAKEAWAYS

- No matter technologies which Member States plan to adopt, either large reactors or Small Modular Reactors, Electrical Grid plays important role for the reliable operation of NPPs, Offsite power (Electrical Grid) should always be considered as the preferred power supply to NPPs, including SMRs.
- The role of off-site power for the reactors with passive safety features has shifted from immediate safety dependency to operational and recovery support. So far, based on early experiences from Member States, but no significant differences have been observed in off-site power supplies arrangement for SMRs compared to large NPPs.
- The IAEA provides extensive publications, guidance, and operational experience to support the integration of NPPs into Electrical Grid. Various IAEA programs are available to assist Member States in successfully connecting their first Small Module Reactors to the Electrical Grid.

Thank you!

Email: Q.yu@iaea.org