U.S. Variable Generation Integration Study Modeling Methodologies and Applications

美国波动性电源并网研究模型方法及应用

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General Description of Models Used in U.S. Related to Electric Power美国电力系统模型工具概述

- Capacity Expansion Planning Models 扩容规划模型
  - Long term capacity expansion for generation and, sometimes, limited representation of transmission
  - 长期发电容量增长，有时也涉及输电方面考虑
  - Simplified dispatch and operations algorithms, though still sometimes 8760 hours
  - 简化调度运行算法，虽然有时仍用8760小时
  - Used for broad picture high-penetration renewable energy studies, and utility resource planning
  - 用于高比例可再生能源研究和电力资源规划
  - not used for detailed, operational RE integration studies
  - 不能用于详细的、运行层面的可再生能源并网研究
  - Examples例如: ReEDs, Switch, Strategist, CREAM-EDO

General Description of Models Used in U.S. Related to Electric Power美国电力系统模型工具概述

- Production Cost Simulation Models生产成本模拟模型
  - Used for optimization of dispatch and operations
  - 用于调度与运行优化研究
  - Used for detailed, operational RE integration
  - 用于详细的、运行层面的可再生能源并网研究
  - detailed representation of plants, flexibility, etc. with hourly or even sub-hourly representation
  - 对电厂、灵活性等有详细展现：小时级甚至次小时级
  - Not used for capacity expansion
  - 不能用于扩容研究
  - Examples例如: GE MAPS, Plexos, GridView, Promod

General Description of Models Used in U.S. Related to Electric Power, cont.美国电力系统模型工具概述

- Load Flow Models潮流模型
  - Ensuring reliability of transmission system to meet N-1 conditions
  - 确保输电系统的可靠性满足N-1 条件
  - Snapshot of time, like hour of peak demand or minimum net load
  - 时间快照，如峰荷小时或最低净负荷
  - Example例如: GE PSLF

Development of multiple models driven, at least in part, by desire to limit computational time and cost. With advances in computing power, expect to see these models used together, such as capacity expansion models and production cost models.
开发众多模型的初衷是减少运算时间和成本。随运算能力的提高，可预见扩容和生产模拟这些模型的配合运用。

详见以下NREL报告
See NREL report at
http://www.nrel.gov/docs/fy14osti/61185.pdf for more information.

Table 1. Models Discussed in this Report

Model Name	Primary Reference	Description	Institution
EGEAS (Electric Generation Expansion Analysis System)	Rastler (2011)	Dynamic programming model used for production costing and generation-expansion planning in the United States.	Electric Power Research Institute (EPRI)[3]
ENERGY 2020	SSI and PAC (n.d.)	System dynamics model that explores the energy supply/demand balance across multiple sectors and regions in North America.	Systematic Solutions Inc.
EPPA (Emissions Prediction and Policy Analysis)	Morris (2008)	Computable general equilibrium (CGE) model that explores the interaction of multiple energy and non-energy sectors for multiple regions around the world.	Massachusetts Institute of Technology
GCAM (Global Change Assessment Model)	PNNL (2012)	Partial-equilibrium model designed to examine long-term, large-scale changes in global and regional energy systems.	Pacific Northwest National Laboratory (PNNL)
IPM (Integrated Planning Model)	EPA (2013)	Deterministic linear programming model of the electric-power sector for multiple regions in North America.	ICF International
LIMES-EU	Haller et al. (2012)	Linear programming model of electricity-sector evolution for Europe, the Middle East, and North Africa.	Potsdam Institute for Climate Impact Research (PIK)
MARKAL (Market Allocation Model)	Loulou et al. (2004)	Linear programming model of both the supply and demand sides of the energy system with a flexible regional structure applicable to any spatial extent.	Brookhaven National Laboratory
NEMS (National Energy Modeling System)	EIA (2013)	Economic equilibrium model for the multi-sector energy system of the United States.	U.S. Energy Information Administration
PERSEUS-RES-E	Rosen (2007)	Linear programming model that optimizes the evolution of the electric power sector in Europe.	Universitätsverlag Karlsruhe (Germany)
PLEXOS LT Plan	Energy Exemplar (2013)	Mixed-integer programming model that integrates long-term electric sector planning optimization with detailed operational optimization for regional systems.[4]	Energy Exemplar
ReEDS (Regional Energy Deployment System)	Short et al. (2011)	Deterministic linear program optimization model of the deployment of electric-generation technologies and transmission infrastructure throughout the contiguous United States.	National Renewable Energy Laboratory (NREL)

[3] EGEAS was originally developed for EPRI by the Massachusetts Institute of Technology and the Stone & Webster Engineering Corporation.
[4] PLEXOS LT Plan has been used to model regions including New Zealand (MMA 2007), Australia (Lilley et al. 2009; Malla 2012; Nweke 2012), and Spain (Panagiotakopoulou n.d.).

Model Name	Primary Reference	Description	Institution
ReMIND-R	Luderer et al. (2011)	General equilibrium model that optimizes the welfare of the integrated energy-economy-environment system around the world.	PIK
REMix (Renewable Energy Mix for Sustainable Electricity Supply)	Scholz (2012)	Linear programming model that determines the cost-optimal electricity supply mix for the European Union (EU) and North Africa.	German Aerospace Center (DLR)
RPM (Resource Planning Model)	Mai et al. (2013a)	Mixed-integer linear programming model with high spatial and temporal resolution that can be used for mid- and long-term scenario planning of regional power systems.	NREL
RREEOM (Regional Renewable Electricity Economic Optimization Model)	Budischak et al. (2013)	Optimization model for evaluating high renewable penetration with a reliable least-cost capacity mix for the PJM system in the eastern United States.	University of Delaware
SEDS (Stochastic Energy Deployment System)	Short et al. (2006)	Stochastic simulation model of the U.S. energy markets designed to explore how the U.S. energy economy will evolve in response to the development of new technologies.	NREL
SWITCH-WECC[5] (Solar, Wind, Hydro and Conventional Generators and Transmission)	Johnston et al. (2013)	Mixed-integer linear programming[6] model for least-cost generation, storage, and transmission capacity expansion for the electric-power sector in western North America.	University of California, Berkeley
THEA (The High temporal resolution Electricity-market Analysis-model)	Nicolosi (2012)	Decomposed linear optimization model for investment planning of the electric-power sectors in Texas and Germany with hourly dispatch.	Universität zu Köln, Germany
US-REGEN (United States Regional Economy, Greenhouse Gas, and Energy Model)	EPRI (2013)	CGE model that combines a mixed complementarity problem (MCP) macroeconomic model with a quadratic complementarity problem (QCP) electric sector investment and dispatch model for the United States.	EPRI
WASP-IV (Wien Automatic System Planning – Version 4)	IAEA (2001)	Dynamic-programming model to analyze the economic optimal generation expansion plan for the electric power sector of a user-define spatial extent.	International Atomic Energy Agency (IAEA)[7]

[5] The version of SWITCH referenced here models the area associated with Western Electricity Coordinating Council (WECC) service territory. There also exists a version of SWITCH specifically for California (Fripp 2012).
[6] The traditional mixed-integer linear programming formulation for SWITCH-WECC can be relaxed and run as a linear program as demonstrated by Mileva (forthcoming) and Nelson (2013).
[7] WASP-IV was originally developed for IAEA by the Tennessee Valley Authority and Oak Ridge National Laboratory.

Elements of a Variable Generation Integration Study
波动性电源并网研究要素

- Mesoscale models for projected wind and solar generation and forecasts
- 中尺度模型用于研究风电太阳能发电和预测
- Statistical analysis统计分析
- Load flow modeling for transmission潮流模型用于输电研究
- Production cost modeling生产成本模型
- Determination of capacity value确定容量价值
- Emissions, wear and tear, and cost impacts of increased cycling of fossil fuel plants
- 排放、劳损、因增加火电机组循环带来的成本影响
- Dynamic transient studies 暂态研究
- Frequency and stability analysis调频与稳定性分析

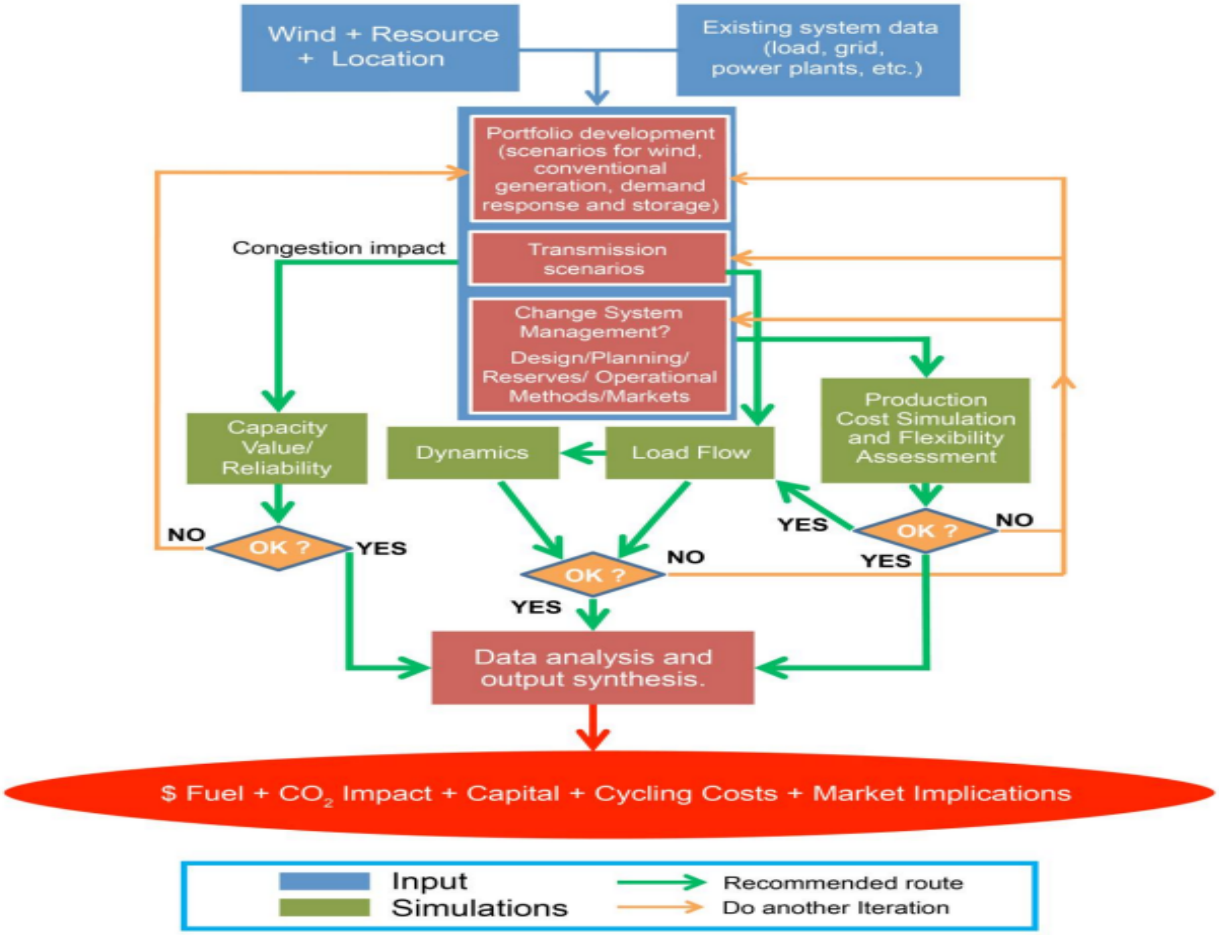


Figure i. Contents of a wind integration study

http://www.ieawind.org/index_page_postings/100313/RP%2016%20Wind%20Integration%20Studies_Approved%20091213.pdf

Where Does the Data for a Variable Generation Integration Study in the U.S. Come From?美国波动性电源并网研究的数据来源

- Government sources 政府来源(EIA, FERC, EPA)
- Non-disclosure agreements 勿泄露协议
- Transmission planning process open to the public. Scenarios and assumptions are debated and agreed to. Stakeholders can request transmission providers to perform specific transmission studies during "study windows" 输电规划制定过程公开。情景、假设过程要经过辩论并达成共识。利益相关方可以要求输电方在规划过程中开展专项输电研究。
- Wind and solar resource databases are posted on the NREL web site风能和太阳能资源数据发布在NREL网站上。
- *Data availability and study transparency ensures robustness of VG integration studies and increases the chance of industry and public acceptance of study results*数据的充分获取和过程的透明公开确保了波动性电源并网研究的说服力也提高了行业和公众接受研究成果的可能性。

Mesoscale Modeling中尺度模型

- Qualities of high quality wind and solar data sets
  高质量的风能和太阳能数据
  - High spatial resolution 高空间分辨率 (e.g., 2 km)
  - High time resolution高时间分辨率 (e.g, 5 minutes)
  - Validation against data from met towers, actual wind plants or clusters of regional aggregation of wind plants数据核验：测风塔数据与风电场或风电区（一片区域的几个风电场集合）实际数据
  - Forecasts at multiple time levels (1, 4, 6 and 24 hour resolutions)多时间尺度的预测
  - Forecasts trained with actual VG production data and calibrated with real forecast errors比对、校准：预测结果与实际发电数据及实际预测误差
- High resolution VG data sets will better represent geographic diversity of VG and a more precise representation of variability and uncertainty高分辨率数据能更好地反应波动性电源的地理分布也更准确地反应其波动性和不确定性
- Costs can range from $10K for a 15 km dataset to $1 million for a 2 km dataset covering three years.数据价格高低不等，三年数据的价格可能是1万美元/15平方公里，也可能是1百万美元/2平方公里

*Memo and presentation on the availability, quality and cost of wind resource data, prepared by Justin Sharp of Sharply Focused LLC, is available from the Energy Foundation of China and explains these issues in more detail*能源基金会曾给国内提供过由美国专家Justin Sharp先生整理的一份材料，描述了美国风资源数据的获取、质量和价格

Evolution of Integration Studies

- Can We Do This?我们能做到吗?
- Utility-by-utility focus各有侧重
- Development of mesoscale model data中尺度模型数据体系
- Higher penetration of wind and, increasingly, solar高比例风电和太阳能
- Regional studies (e.g., Western Wind and Solar Integration Study, Eastern Wind Integration and Transmission Study)区域并网研究（如，西部风电和太阳能并网研究和东部风电并网与传输研究）

A Few Recent Trends in Variable Generation Integration Studies in the U.S.美国波动性电源并网研究的发展趋势

- Higher penetration levels更高的接入比例
  - 40% wind in Minnesota study
  - 明尼苏达州40%比例风电的研究
- Effects of cycling运行影响
  - Phase 3 of the Western Wind and Solar Integration Study found that 33% renewables increases cycling costs between $35 million and $157 million in the West, as compared to $7 billion in fuel cost savings from higher levels of VG
  - 西部风电和太阳能并网研究发现，虽然接入33%的可再生能源在西部会使机组循环的成本上升3500万美元到1亿5700万美元；然而，可再生能源发电带来的燃料成本节约却高达70亿美元
  - Five scenarios, all 33% VG but varying levels of wind and solar
  - 5种情景都达到了33%的可再生能源接入比例，只是风电和太阳能的比例有所不通
  - Production cost modeling the primary tool—generation commitment and dispatch, emissions, costs and transmission path flows were the outputs
  - 生产成本模型为主要工具—可得出机组组合和调度、排放、成本、输电通道等产出


GE Energy Consulting

Minnesota Renewable Energy Integration and Transmission Study

Final Report

Prepared for:

- The Minnesota Utilities and Transmission Companies
- The Minnesota Department of Commerce

Prepared by:

- GE Energy Consulting, *with contributions by:*
  - The Minnesota Utilities and Transmission Companies
  - Excel Engineering, Inc.
  - MISO

In Collaboration with MISO

October 31, 2014

A Few Recent Trends in Variable Generation Integration Studies in the U.S., cont.美国波动性电源并网研究的发展趋势

- Frequency Response and Transient Stability频率响应和暂态稳定
  - Concern is displacement of conventional generation by VG will result in deterioration of frequency response and transient stability重点关注可再生能源替代传统能源会对频率响应和暂态稳定有影响
  - GE/NREL study basically found that frequency response and transient stability can be maintained with high levels of VG with transmission upgrades, and further improved with synchronous condenser conversions and frequency response controls on VG
  - GE/NREL的研究认为基本可以通过输电线路升级和对波动性电源加强同步调相机转换和频率响应控制来解决接入高比例可再生能源带来的频率响应和暂态稳定影响
  - Measured effect on grid with different levels of VG and the loss of two nuclear plants (2,750 MW); the loss of three nuclear plants; the loss of all solar DG; and a three-phase fault at a 500 kV transmission line
  - 评估接入不同比例可再生能源和减少两台核电机组（2750兆瓦）对电网的影响；减少三台核电机组；减少所有分布式太阳能；一条500千伏输电线路发生三相短路故障

Western Wind and Solar Integration Study Phase 3 – Frequency Response and Transient Stability: Executive Summary

N.W. Miller, M. Shao, S. Pajic, and R. D'Aquila
GE Energy Management
Schenectady, New York

NREL Technical Monitor: Kara Clark

Link to full report

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Subcontract Report
NREL/SR-5D00-62906-ES
December 2014

APPENDIX
附录

Load Flow Analysis潮流分析

- Base system plus projected transmission additions
- 基础系统加上预期的输电增量
- Performance of transmission grid in steady state (peak load), N-1 conditions, and contingency conditions
- 在稳定状态下（负荷峰值）输电线路的性能，N-1情况下，应急情况下
- Measure whether transmission is overloaded at particular locations and at what times
- 衡量在特定的地点和时段线路是否过载
- Add transmission lines, transmission upgrades, and transformers additions or replacements
- 增加线路，输电线路升级，增加或更换变压器

Production Cost Models生产成本模型

- More recent integration studies simulate both Day-Ahead Security Constrained Unit Commitment and Real-Time Constrained Economic Dispatch最近的并网研究在模拟日前安全约束机组组合和实时约束经济调度
  - “Interleaved” modeling, with one simulation feeding into another“交错”建模与交互仿真
  - Captures forecast uncertainties between day-ahead and real-time捕捉预测不确定性的规律：日前预测与实时之间
- Include current generating units, known and projected capacity additions and retirements, additional renewables needed for meeting scenario or government-required targets综合考虑满足一定情景或者达到政府规定目标要涉及的各种因素，包括现有发电机组，预计增加和淘汰（退役）的容量，新增可再生能源需求等
- Load from actual year (e.g., 2006), then scaled by projected load growth to future year (e.g., 2020).基于当年负荷（如2006年）放大计算出未来（如2020年）负荷增长
- Model outputs by scenario: annual energy production by type of generation, renewable energy curtailment, risk of reserve violations and unserved load hourly dispatch, emissions, fuel consumption, production costs.依情景模拟产出：不同类型电源的年度发电量、可再生能源限制出力、备用不足风险、小时级调度无法满足负荷的风险、排放、燃料消耗、生产成本等
- VG curtailment可再生能源限制出力
  - Available VG capacity exceeds transmission capacity, reflecting N-1 or transmission outage
  - 可再生能源的发电量超出传输能力，可能造成N-1或传输中断
  - Aggregate VG is more than what can be accommodated, even if other generation at minimum and exports are maximized
  - 可再生能源总发电量超出消纳能力，即便充分压低其他电源和最大外送
- Hourly results will identify “periods of interest” for more intensive study on a sub-hourly basis
- 小时级结果可以为开展小时内程度的更细研究找出研究的兴趣时段（重点时段）

Western Wind and Solar Integration Study, Phase II (GE/NREL)西部风能与太阳能发电并网研究二期

- More cycling of fossil-fueled generation can contribute to thermal and pressure stresses, resulting in component failures, higher O&M costs and, perhaps, higher emissions of CO2, NOx, and SO2
- 增加传统机组的循环启停会增加热应力和压应力，引起组件故障、提高运行成本、还可能导致CO2，NOx，SO2排放的增加
- More VG affects the operations of other generating plants and induces more starts and stops, ramping and cycling
- 波动性电源的增加对其他机组的运行有影响，增加启停、爬坡和循环需求
- Study found that 33% renewables increases cycling costs between $35 million and $157 million in the West, as compared to $7 billion in fuel cost savings from higher levels of VG
- 研究发现，虽然接入33%的可再生能源在西部会使机组循环的成本上升3500万美元到1亿5700万美元；然而，可再生能源发电带来的燃料成本节约却高达70亿美元
- Seven categories of coal and gas plants were created from proprietary data set of cycling costs
- 建立了七类煤电和气电的循环成本专项数据库
- U.S. Environmental Protection Agency (EPA) maintains unit-specific emissions data for large generating units.
- 美国环保部还保留了各类大型机组的排放数据

Western Wind and Solar Integration Study Phase II, cont. 西部风能与太阳能发电并网研究二期

- Production cost modeling the primary tool—generation commitment and dispatch, emissions, costs and transmission path flows were the outputs
- 生产成本模型为主要工具—可得出机组组合和调度、排放、成本、输电通道等产出
- Five scenarios 五种情景
  - No renewables没有可再生
  - Base renewables for 2020: 9.4% wind, 3.6% solar
  - 2020可再生基础情景：9.4% 的风电和 3.6% 的太阳能
  - High wind: 25% wind, 8% solar
  - 高风电情景：25%风电，8%太阳能
  - High solar: 25% solar, 8% wind
  - 高太阳能情景：25%太阳能，8%风电
  - High mix: 16.5% wind, 16.5% solar
  - 混合高比例：16.5%太阳能，16.5%风电
- Dispatch: day-ahead with day-ahead wind and solar forecasts, with all coal and nuclear committed day-ahead; 4-hour ahead for committing combined cycle and gas steam units, with 4-hour ahead wind and solar forecasts; and 5-minute dispatch
- 调度：风电和太阳能的日前预测，与日前排好的全部煤电和核电； “4小时前”用于安排联合循环燃气机组，与4小时前风电和太阳能预测；5分钟级调度

Western Wind and Solar Integration Study, Phase III (GE/NREL) 西部风能与太阳能发电并网研究三期

- Concern is displacement of conventional generation by VG will result in deterioration of frequency response and transient stability
- 怀疑可再生能源替代传统能源会对频率响应和暂态稳定有影响
- GE/NREL study basically found that frequency response and transient stability can be maintained with high levels of VG with transmission upgrades, and further improved with synchronous condenser conversions and frequency response controls on VG
- GE/NREL的研究认为基本可以通过输电线路升级和对波动性电源加强同步调相机转换和频率响应控制来解决接入高比例可再生能源带来的频率响应和暂态稳定影响
- Data and Assumptions:数据和假设
  - Wind and solar capacity and production data by location
  - 不同地点的风电和太阳能容量与发电量数据
  - Light load scenarios with base and high renewables, and summer peak demand scenarios with base and high renewables
  - 低负荷情景与基础和高比例可再生能源，夏季负荷需求情景与基础和高比例可再生能源
- Power flow and transient stability simulation tool (GE's PSLF)
- 潮流和暂态稳定模拟工具(GE的 PSLF)
- Transmission planning database from the Western Electricity Coordinating Council (WECC)
- 西部电力协调委员会（WECC）的输电规划数据库

Western Wind and Solar Integration Study, Phase III cont. 西部风能与太阳能发电并网研究三期

- Measured effect on grid with different levels of VG and the loss of two nuclear plants (2,750 MW); the loss of three nuclear plants; the loss of all solar DG; and a three-phase fault at a 500 kV transmission line
- 评估接入不同比例可再生能源和减少两台核电机组（2750兆瓦）对电网的影响；减少三台核电机组；减少所有分布式太阳能；一条500千伏输电线路发生三相短路故障
- Simulated grid operations with active power control and inertial control on wind plants and utility-scale solar plants, and with the addition of energy storage
- 模拟风电场和集中式太阳能电站加以有功控制和惯性控制后的电网运行，以及加上储能后的运行

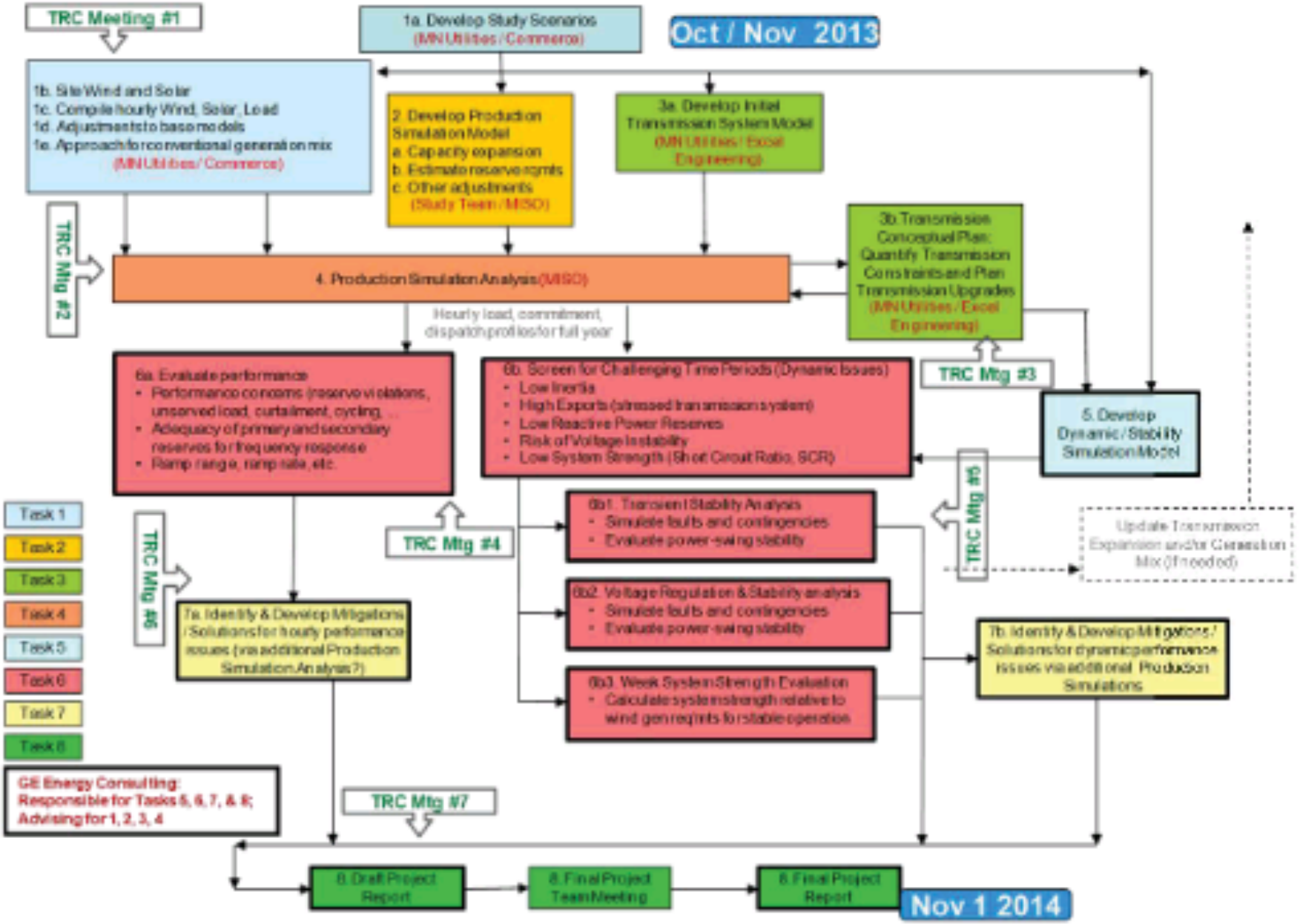
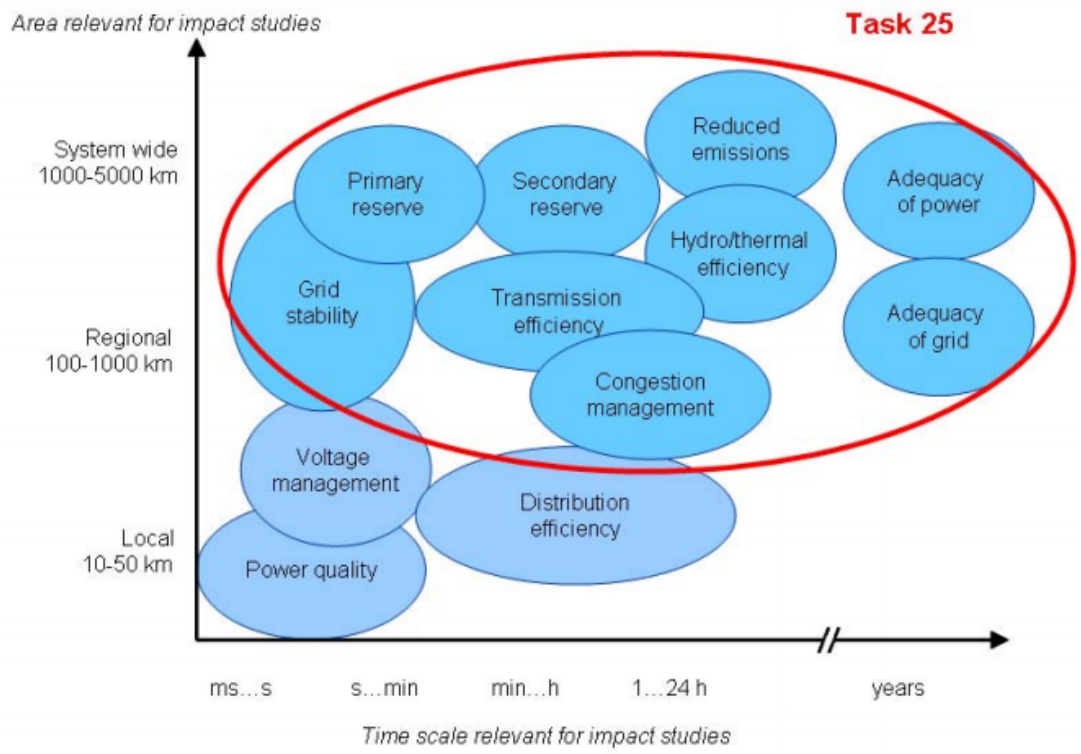


Figure 2-1 Flowchart of Project Tasks

with increased variability and uncertainty. Market rules will also have an impact, as technical costs can be different from market costs.



http://www.ieawind.org/AnnexXXV/PDF/Final%20Report%20Task%2025%202008/T2493.pdf