Integrated Expansion Planning for Optimising Hydropower Development

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Background

When optimising the expansion of power supply systems the economic objective is to minimise the total investment and operating costs over the planning period. However, due to the complexity of the problem, it has been customary to optimise generation additions and then design a complementary transmission system. To a large extent this approach has been dictated by a lack of computer software capable of simultaneously optimizing both aspects.

Commercial incentives to develop such software have been reduced by lending agencies continuing to promote the use of freely available generation planning programs such as WASP (Wein Automatic System Planning), originally developed in the 1970's to promote nuclear power. However, even the latest versions of WASP suffer from major limitations when applied to hydro-thermal systems. These include an inability to ensure the optimal introduction of candidate hydro plants (relying on a selection being made from two pre-ordered lists), to take account of project interdependencies, and the need to aggregate electricity demands having disparate supply benefits and deficit (unserved energy) penalties.

For countries with an extensive 'mesh' transmission system the single demand area assumption may be acceptable. However, with the 'radial' systems associated with hydro plants remote from principal demand centres, the degree to which transmission losses, costs and capacity constraints may impinge on the (least cost) dispatch of generation plant can be significant. The development of international 'power pools' further complicates the situation, as decisions increasingly need to be made by individual countries as to whether to import and/or export electricity and, if so, at what tariffs.

Whilst the investment costs of connection to a predetermined transmission system node can be included in those of candidate generation plant, continuous improvements in computer capabilities, and the availability of increasingly efficient optimisation algorithms, suggest that the separation of the generation and transmission aspects of expansion planning may no longer be justified. Examples are where strengthening an existing transmission system or importing electrical energy may be more cost effective than providing new generation facilities, and when export possibilities justify the introduction of greater generation capability than required solely to satisfy domestic demands.

Similarly, when optimising the expansion of hydro-thermal and renewable generation systems adequate account needs to be taken of component dependencies, including choices between hydro project variants, and the effects of constructing upstream storage reservoirs. For example by evaluating, in a system context, the relative economics associated with a relatively low cost 'run-of-river' development and those of a more expensive storage project providing higher levels of reliable ('firm') energy.

Such considerations have prompted the recent development by Power & Water Systems Consultants Ltd. (PWSC) of computer software capable of optimizing integrated expansion plans for multiple demand systems, whilst taking explicit account of project dependencies and budget constraints. As described below, Program CAPRICORN consists of Optimization and Simulation modules which share a common set of input data files.

The CAPRICORN Optimization Module

The Optimization Module employs Mixed Integer Linear Programming (MILP) to optimize the selection and commissioning dates of candidate generation plants and transmission lines, as well as import and export quantities, consistent with meeting forecast electricity demands at least net discounted cost. The expansion planning period can be divided into yearly or monthly time steps, or a combination of both, and up to 8 load blocks used to represent electricity demands in each time step, with a minimum of three being required to model peak, mid and base loads.

The optimization is able to take account of:

- the energy generation costs (per MWh) and capacity costs (per MW) associated with existing and candidate generation plant;
- for hydro plants, maximum capacities and energy availabilities associated with up to 5 Hydrological Conditions corresponding to, for example, very dry (‘firm’), dry, average, wet and very wet years or sets of years;
- mutual exclusivities e.g. Project A or Project B can be built, but not both e.g. hydro project variants;
- mutual dependencies e.g. Project C must be commissioned before Project D;
- hydro plant energy dependencies i.e. changes in ‘firm’ and ‘average’ energy availabilities at existing or candidate hydro plant E which would result from commissioning candidate hydro plant F;
- minimum (annual) energies to be dispatched e.g. as stipulated under a Power Purchase Agreement;
- for other non-hydro generation plants, maximum and minimum dispatch capacities (MW) and energy outputs (MWh);
- for transmission lines, maximum capacity (MW) and carriage (e.g. ‘wheeling’) costs per MW and MWh, and losses (as percentage of input energy);
- differential supply benefits and ‘failure to supply’ penalty costs associated with individual electricity demand areas, including exports;
- (monthly) investment costs for candidate generation plants and transmission lines, split into local and foreign currency components;
- economic lifetimes and decommissioning costs;
- budget limits on annual investment costs, investment plus operating costs, investment plus operating plus penalty costs and total net costs (investment plus operating plus penalty costs minus supply benefits);
- the specified (base) discount rate, variable operating cost inflation rates, period of economic analysis i.e. additional to the expansion planning period, and Hydrological Condition weighting factors.

The Linear Programming formulation involves the definition of the decision variables to be optimised and ‘less than or equal’ (<=), ‘greater than or equal’ (>=) and ‘equality’ (=) constraints associated with individual and multiple load blocks and time steps.

Commissioning Variables (CV’s) are used to optimize the fraction of each generation plant, transmission line or demand brought into service in each time step. The associated objective function coefficients are the unit investment costs per MW less any salvage benefits that would accrue at the end of the analysis period, discounted to the start of the planning period.

The costs of meeting electricity demands in each time step and load block, and under each Hydrological Condition, are minimized by optimising the outputs of each generating plant, the flows in each transmission line, and any demand area deficits.

In addition to constraints used to impose limits on maximum and minimum generation plant outputs and transmission line flows in each load block, additional <= constraints are used to ensure that for the sum of the CV's for each generation plant, transmission line and demand area are less than or equal to 1, and that budgetary limits are observed. >= constraints are used to impose lower limits on energy production, such as may be incorporated in Private Power Agreements. It can be noted that the facility to set supply benefits as well as penalty costs on a demand area basis means that a 'global' least cost solution, and the optimal level of exports and imports in each time step, can be obtained.

Development Example

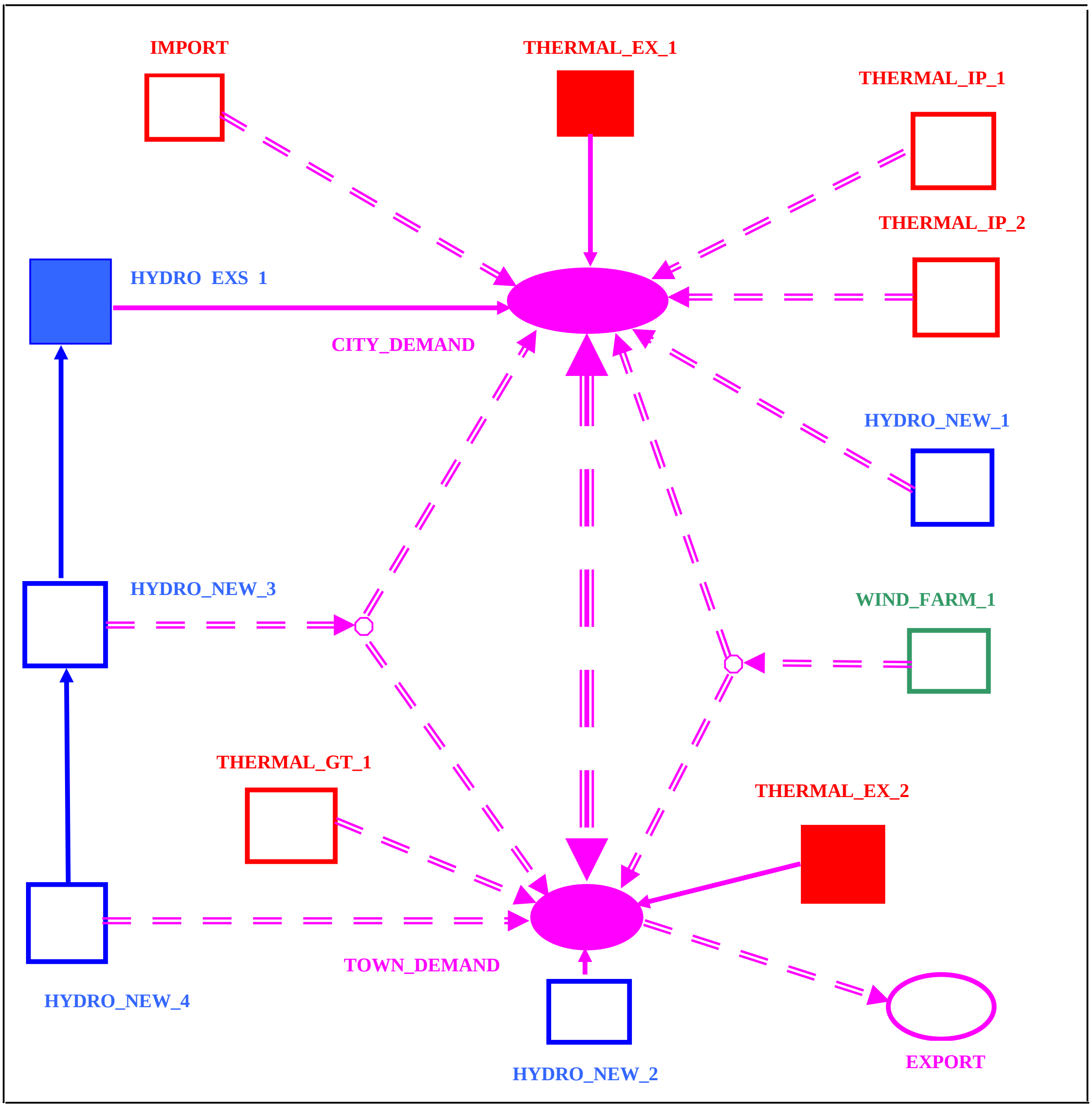

Figure 1: Development Example System

The theoretical system shown in Figure 1 was used to develop the CAPRICORN Optimisation Module, with ‘existing’ components being shown as solid shapes and candidate additions with dashed outlines.

The initial 2016 system consists of the 500 MW hydro plant HYDRO_EXS_1 and 250 MW thermal plant THERMAL_EX_1 supplying CITY_DEMAND, and the 150 MW thermal plant THERMAL_EX_2 supplying TOWN_DEMAND *via* existing transmission lines. The two demand areas are not connected, and the existing thermal plants are to be retired in 2021 and 2023 respectively. With the maximum capacities and earliest commissioning years shown in square brackets, the development options are as follows:

- the commissioning of:
    - HYDRO_NEW_1 [250 MW - 2020] and HYDRO_NEW_2 [150 MW - 2023] which, although not linked hydraulically, are mutually exclusive;
    - HYDRO_NEW_3 [1000 MW - 2021] and HYDRO_NEW_4 [750 MW - 2023] which are both located upstream of the existing HYDRO_EX_1;
    - WIND_FARM_1 [100 MW - 2018] which can supply the CITY_DEMAND or TOWN_DEMAND or both;
    - mutually exclusive IPP plants THERMAL_IP_1 [250 MW - 2018] and THERMAL_IP_2 [225 MW - 2019], having different energy costs and minimum annual energy conditions and 10 year contracts;
    - THERMAL_GT_1 [250 MW - 2018] linked to TOWN_DEMAND.
- inter-connecting CITY_DEMAND and TOWN_DEMAND [2018];
- importing electricity *via* a connection to CITY_DEMAND [2017];
- exporting electricity *via* a connection from TOWN_DEMAND [2020];
- alternative transmission routings e.g. WIND_FARM_1 to CITY_DEMAND [2018] ,or to TOWN_DEMAND [2019].

For a 15 year expansion planning period, annual time steps, 3 load blocks and 2 Hydrological Conditions, the CAPRICORN formulation results in a linear programming problem with 2,450 decision variables to be optimised (of which 159 are CV’s), 2,470 <= constraints, 88 >= constraints and 1,141 = constraints.

MILP solution algorithms initially determine the optimum ‘Continuous’ LP (CLP) solution before obtaining the best mixed integer solution by systematically fixing the integer variables to permitted values and re-solving. As a result, the times required to solve MILP problems are typically much longer than those required to find the initial continuous solution.

While the concept of building, say, 0.37 of a hydro plant is clearly unrealistic, it can be noted that CLP solutions may, in themselves, provide useful information. For example, by indicating, for each expansion planning year, the optimum capacities of new transmission lines and ‘generic’ thermal plants i.e. those that can be ‘repeated’ over the expansion planning period, the economic quantities of electrical energy to be imported and exported, and even the optimum staging of large capacity hydro plants.

Using a 2.3 GHz Quad Core™ Intel© i7 processor and ‘lp_solve’ Version 5.5.2.0 (please see Acknowledgement), an optimum continuous solution for the example system described above was obtained in 4 seconds. If the CV’s for all candidate hydro plants, thermal plants, transmission lines and demands are constrained to binary values some 3 minutes 57 seconds were required to reach the optimal solution.

In common with most hydro-thermal systems, expansion of the development example is energy rather than capacity constrained and Figure 2 compares, for a particular data set, the system ‘firm’ energies corresponding to optimised CLP and MILP expansion plan solutions.

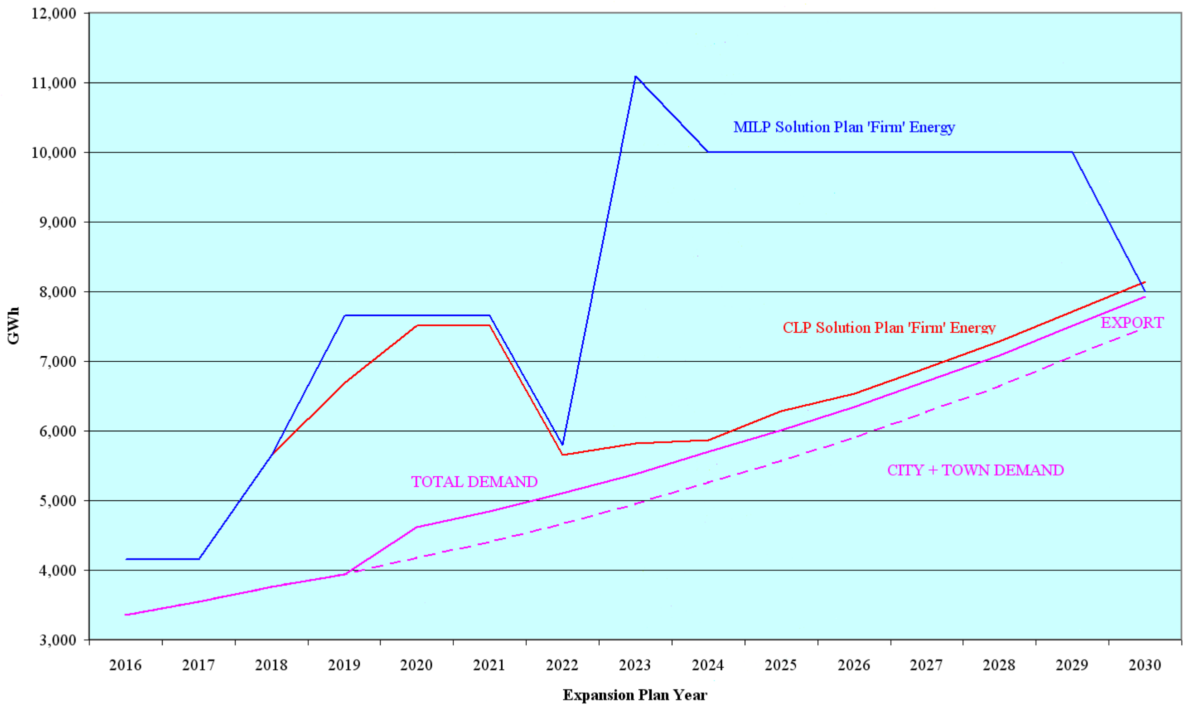

Figure 2: Firm Energies of CLP & MILP Expansion Plans for the Development System

In both cases 2018 sees the inter-connection of the CITY and TOWN demands and the early commissioning of THERMAL_GT_1, due to its having much lower operating costs than the existing thermal plants. Exports begin in 2020 and are maintained until the end of the planning period.

The two plans differ in that the CLP solution brings in 129 MW of THERMAL_IP1 in 2019, whereas under the MILP plan its maximum capacity of 250 MW is commissioned. In both cases this source of generation is taken out of service in 2030.

Following retirement of the existing thermal plants THERMAL_EX_1 and THERMAL_EX_1, the CLP plan calls for the staged commissioning of the HYDRO_NEW3 and HYDRO_NEW4 plants from 2023 whereas they are commissioned in their entirety under the MILP plan. Under the CLP plan the staged introduction of HYDRO_NEW_2 would begin in 2030.

It can be noted that, as from 2023, the system ‘firm’ energy associated with the CLP plan is in excess of the total demand, reflecting the impact of transmission constraints and losses.

As expected, since only the commissioning of complete components is permitted under the MILP plan, there are much larger differences between the available system ‘firm’ energies and the demands to be met in each year. However, it can be noted that such excesses can sometimes be justified if they result in significantly lower operating costs under ‘average’ conditions.

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Ethiopian Example

As described in a previous paper[1] the Ethiopian Power System Expansion Masterplan Study, carried out between 2012 and 2014, involved the derivation of generation expansion plans covering the 25 year period from 2012 to 2037 using WASP.

As identified within that study, the potential Ethiopian system consisted of 11 existing, 6 committed, and 27 candidate hydro plants, plus 2 existing, 25 committed and 9 candidate conventional thermal, wind, solar and biomass generation plants, of which 7 were treated as 'generic' with defined maximum installed capacities and annual increments. There are existing and potential opportunities to export electrical energy to Djibouti, Egypt, Sudan, Kenya and Tanzania, but for this application of CAPRICORN no attempt was made to optimise such exports or model development of the transmission system.

For the 25 year expansion planning period, annual time steps, 3 load blocks and 2 Hydrological Conditions, the LP formulation resulted in 11,085 decision variables (of which 647 were CV's), 13,877 <= constraints, 108 >= constraints and 182 = constraints. Typically, LP solution times increase with both the number of variables and the number of constraints and, for this problem, 'lp_solve' was able to obtain the optimum continuous solution in 20 seconds. If the CV's for all candidate hydro plants and thermal plants were set to binary values, the solution time increased to 1 hour 12 minutes and 51 seconds.

Figure 3 compares the system 'firm' energies corresponding to the CLP and MILP expansion plan solutions, and it can be seen that they are very similar. This is because the forecast demand growth is such that in most years it will be necessary to commission multiple hydro or generic thermal sources of generation and that, *ceteris paribus*, it is preferable to fully exploit a cheaper alternative before introducing one that is more expensive. In other words, in each time step of the CLP solution there is likely to be only one plant with a CV less than 1.

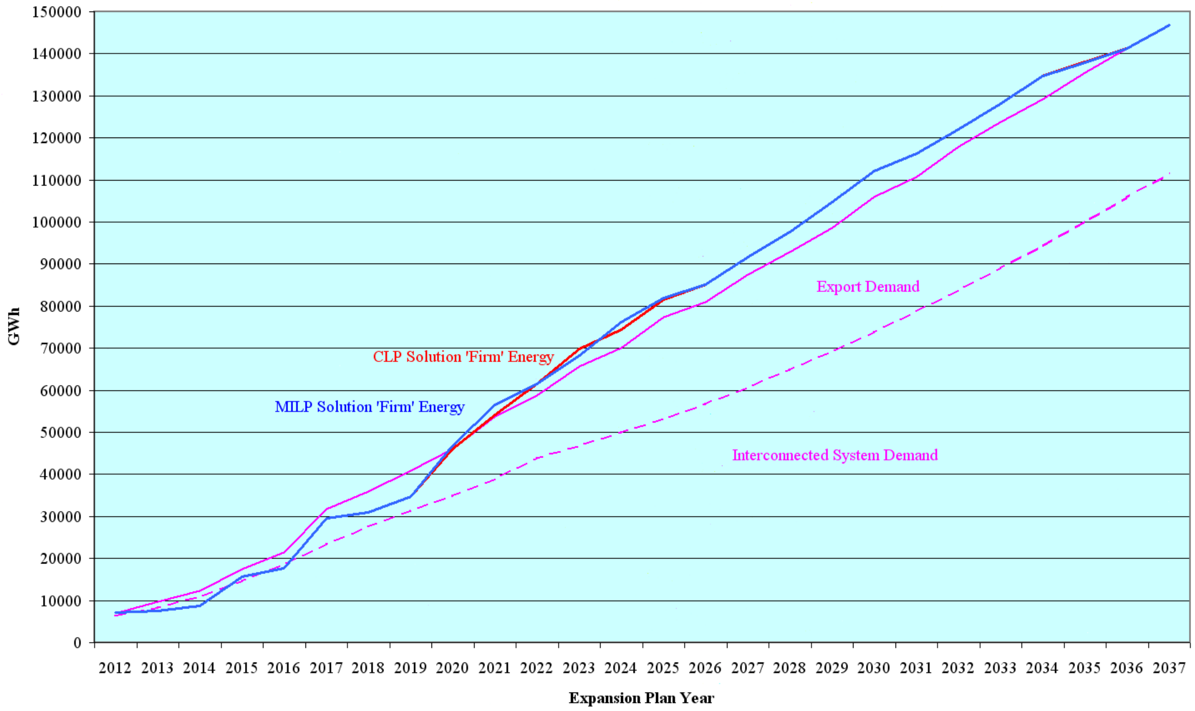

Figure 3 : Firm Energies of CLP & MILP Expansion Plans for the Ethiopian System

The CAPRICORN Simulation Module

Since there are always likely to be non-quantifiable factors to be considered when deriving acceptable expansion plans, solutions obtained using formal optimisation techniques such as MILP can be viewed as starting solutions which may require subsequent refinement. For example, rudimentary transmission system modelling based on load flows and linear losses needs to be followed up with detailed electrical network analyses.

The CAPRICORN Simulation Module, formerly Program EPSIM, permits the very rapid evaluation of expansion plans defined by component commissioning and retirement dates. A monthly time step is employed for deterministic or probabilistic load dispatch optimisations, which can take account of transmission costs and losses as well as supply rationing.

Hydro plant capacity and energy availabilities associated with up to five Hydrological Conditions can be considered, as well as hydraulic interactions between developments. Generation plant capabilities can also be varied as a function of the expansion planning year[1].

As shown in Figure 4, the module also permits the inter-active construction of expansion plans, with the user able to select from pick lists of candidate hydro and thermal (non-hydro) generation plant ranked in accordance with alternative ‘heuristic’ ranking indices such as. £/MW installed, £/MWh (firm and average), etc. These lists also take account of minimum construction times, component dependencies and mutual exclusivities.

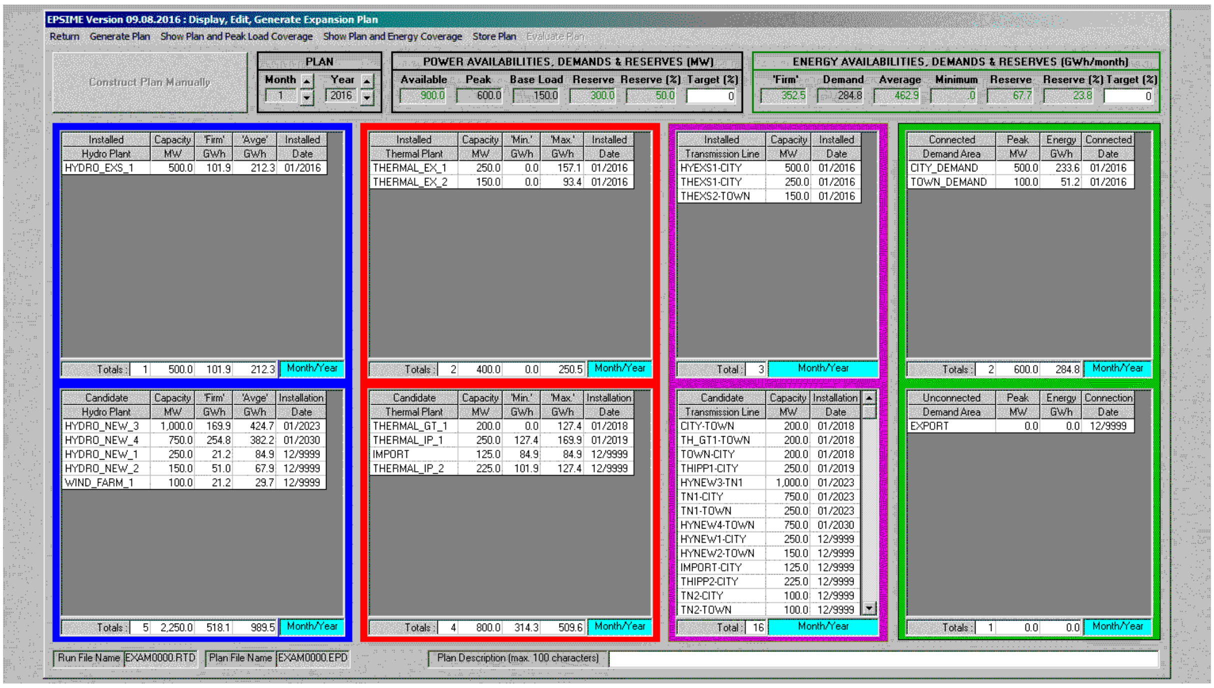

Figure 4 : Display & Interactive Expansion Plan Construction

All economic analyses are carried out on a monthly basis, and extensive facilities are provided for the display of detailed and consolidated results in graphical and tabular form. These include their export in CSV format output files, the storage of alternative expansion plan evaluation results, system component details and electricity demands in Microsoft ACCESS© format, and the display of system development and load dispatch results in ‘mimic’ diagram form.

Conclusions

Continuous advances in computer capabilities, coupled with improvements in the efficiency of mathematical optimisation algorithms, have raised the possibility of simultaneously optimising the future commissioning of generation and transmission systems while taking explicit account of project exclusivities, dependencies and budgetary limits. As described, applications of Program CAPRICORN demonstrate the feasibility of employing Mixed Integer Linear Programming (MILP) formulations to optimise expansion plans for systems involving several thousand decision variables and constraints.

The quoted solution times confirm the computational viability of such an integrated approach to power system expansion planning. They should also encourage conducting multiple optimisation runs to establish the sensitivity of expansion plans to variations in demand forecasts, discount rates, variable (fuel) cost inflation rates, import and export tariffs, PPA conditions, investment costs, construction periods and budget constraints. The ability to take explicit account of project dependencies and exclusivities means that the approach embodied in CAPRICORN is particularly suitable for optimising hydropower development, although it is equally applicable for optimising development of systems without hydro components.

It is, of course, possible to conceive of expansion plan formulations resulting in numbers of decision variables and constraints of higher orders of magnitude than those described. For example, if complex transmission systems are to be modelled or if a large number of monthly planning steps are specified. Commercial packages now exist capable of solving LP problems involving millions of decision variables and constraints, and at least one is able to receive the requisite data in the format produced by CAPRICORN. At the same time, the availability of ever faster computer processors will further enhance the viability of the approach.

The full benefits of such software will be realised when those responsible for power system expansion planning are able to update such plans on a frequent and regular basis. In addition to expansion planning, potential applications of Program CAPRICORN include import and export tariff negotiations, internal tariff setting based on long-term marginal costs, and the comparison and selection of hydro project variants in the context of the recipient system.

Further details of Program CAPRICORN, and its companion program AQUARIUS for optimising the operation of integrated water resource and power systems, can be found at www.pwsc.co.uk

Acknowledgement

PWSC gratefully acknowledges the use of ‘lp_solve’ within Program CAPRICORN and, as requested by the developers, is pleased to provide the following details.

Description	Open source (Mixed-Integer) Linear Programming system
Language	Multi-platform, pure ANSI C / POSIX source code, Lex/Yacc based parsing
Official name	lp_solve (alternatively lpsolve)
Release data	Version 5.5.2.0 dated 11 August 2010
Co-developers	Michel Berkelaar, Kjell Eikland, Peter Notebaert
Licence terms	GNU LGPL (Lesser General Public Licence)
Citation policy	General references as per LGPL
	Module specific references as specified therein

Bibliography

1. **Wyatt, T., Pearce A.J.H. and Thorn D.**
"Planning Development of Ethiopia's Hydropower Resources"
Paper presented at HYDRO 2015 conference on 'Advancing Policy and Practice', Bordeaux, France, October 2015.

Author Profile

Timothy Wyatt graduated from Edinburgh University in 1969 with an Honours degree in Civil Engineering. After 4 years researching the application of simulation and mathematical programming techniques to water resource systems, he spent 6 years in Latin America as a hydrologist and water resources engineer working on Electricity Masterplan studies for Guatemala and Peru, before being appointed project leader for a power system expansion study in Uruguay. He has subsequently analysed hydro-thermal power systems in Sri Lanka, Cameroon, Brazil, Turkey, Tanzania and Ethiopia, and developed the AQUARIUS computer program for simulating and optimising the long and short-term operation of integrated water resource, water supply and power supply systems, and CAPRICORN for simulating and optimising the development of integrated power supply systems. He is the Managing Director of Power & Water Systems Consultants Ltd. (PWSC), which he co-founded in 1983, and has authored a number of papers on operating policy optimisation and development planning.