

## *A Stochastic Programming Model for Power Generation Expansion Planning in Iran*

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### *ABSTRACT*

In this paper, by developing a mixed integer stochastic programming model, total cost of construction of new power generation capacity using various technologies and the cost of generating electricity during a planning horizon is minimized. The demand is considered uncertain in this model and is assumed to follow three possible scenarios. In this study, the country is divided to several regions and the investment decisions are taken for each region in an integrated model. Furthermore, a learning mechanism of technologies is considered in the model, so the cost of investment in technologies will decrease as installed capacity of each technology is increasing. Finally, in order to analyze the output of optimization model, by developing a system dynamic model, the impacts of the proposed plan on some power industry indicators such as cost and profit is shown with respect to each demand scenario.

The resulting capacity expansion plan consists of various power generation technologies among which gas turbine power plant constitutes the biggest part of the expansion plan. Other technologies such as hydro, combined cycle, nuclear, geothermal and wind power plants exist in the expansion plan.

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**KEYWORDS**

Capacity Expansion Planning, Power Industry, Power Generation, Stochastic Programming, System Dynamics

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WASP

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$$\min z = c^T x + \sum_{k=1}^K p_k q_k^T y_k \quad ( )$$

$$st. Ax = b$$

$$T_k x + W y_k = h_k \quad k = 1, \dots, K$$

$$x \geq 0, y_k \geq 0 \quad k = 1, \dots, K$$

K

$P_k$

x

T h q

y

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(CBLD\*BLD)  
 (CBDI\*BDI) ( )  
 (CFXD\*EXD)

(COPD\*OPD)  
 (COPR\*OPR)  
 (COPH\*OPH)  
 PNG\*QNG )  
 (PGO\*QGO POL\*QOL  
 (CUSD\*USD)

$$\begin{aligned}
 \text{Min} \quad & \sum_{y,r,c} \text{CBLD}_{yrc} \cdot \text{BLD}_{yrc} + \sum_{y,r,c} \text{CBDI}_{yerc} \cdot \text{BDI}_{yerc} + \sum_{y,r,c} \text{CFXD}_{yrc} \cdot \text{EXD}_{yrc} \\
 & + \sum_{s \in S} P_s \left\{ \sum_{y,r,D,I} \text{COPD}_{yrDI} \cdot \text{OPD}_{yrDIs} + \sum_{y,r,n} \text{COPR}_{yrn} \cdot \text{OPR}_{yrns} + \sum_{y,r,I} \text{COPH}_{yrI} \cdot \text{OPH}_{yrIs} \right. \\
 & \left. + \sum_{y,r} (\text{PNG}_y \cdot \text{QNG}_{rys} + \text{POL}_y \cdot \text{QOL}_{rys} + \text{PGO}_y \cdot \text{QGO}_{rys}) + \sum_{y,r,I} \text{CUSD}_{yI} \cdot \text{USD}_{yrls} \right\} \\
 & \text{EXD} \quad ( \quad ) \quad ( /
 \end{aligned}$$

CO<sub>2</sub> SO<sub>2</sub> ( )  
 CO2 SO2 ( )

(QNG,QOL,QGO)  
 (SO2,CO2)  

$$\sum_r (\text{QNG}_{rys} \cdot \text{SO2}_{NG} + \text{QOL}_{rys} \cdot \text{SO2}_{OL} + \text{QGO}_{rys} \cdot \text{SO2}_{GO}) \leq \text{ASO2}_y$$
 s y

(OPD)  
 (EXDR) c  
 (PMC) (BDI BLD) PMC 1 LHRS  
 (TRN) CPMR\*EXD

$$\sum_l LHRS_l \cdot PMC_{yrcls} - CPMR_{rc} \cdot EXD_{yrc} \geq 0$$

s y r c

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$$OPD_{yrcls} - EXDR_{yrc} - \sum_{j=1}^y BLD_{jrc} - \sum_{j=1}^y \sum_e BDI_{jeer} \cdot TLOSS_{jer} + PMC_{yrcls}$$

$$+ \sum_g TRN_{yrcls} - \sum_e TRN_{yeers} \cdot TLOSS_{yer} \leq 0$$

s y r l c

ELC

$$OPH_{yrts} - ELH_{yrts} \cdot EXDR_{yrts} - \sum_{j=1}^y ELH_{yrts} \cdot BLD_{jrt} - \sum_{j=1}^y \sum_e ELH_{yelt} \cdot BDI_{jehr} \cdot TLOSS_{jer}$$

$$+ \sum_g TRN_{yrts} - \sum_e TRN_{yehrs} \cdot TLOSS_{yer} \leq 0$$

y r l

ELA

OPD

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c

ELR

OPR

(ELA)

(OPD)

(LHRS)

(HRD)

(FS)

QGO QOL QNG

USD

OPH

TLOSS

$$\sum_{cl} ELA_{yrcl} \cdot OPD_{yrcls} \cdot FS_{r,c,NG} \cdot LHRS_l \cdot HRD_{yrc} / 8297 - QNG_{ryst} \leq 0$$

y c s

$$\sum_c ELA_{yrcl} \cdot OPD_{yrcls} + \sum_e ELR_{yre} \cdot OPR_{yre} + OPH_{yrts}$$

$$+ \sum_l ELI_{yrll} \cdot EXDR_{yrll} + \sum_l \sum_{z=1}^y ELI_{zrll} \cdot BLD_{zrl} + \sum_{le} \sum_{z=1}^y ELI_{zrll} \cdot TLOSS_{zer} \cdot BDI_{zrlr} + USD_{yrts} \geq ELC_{yrts}$$

s r y l

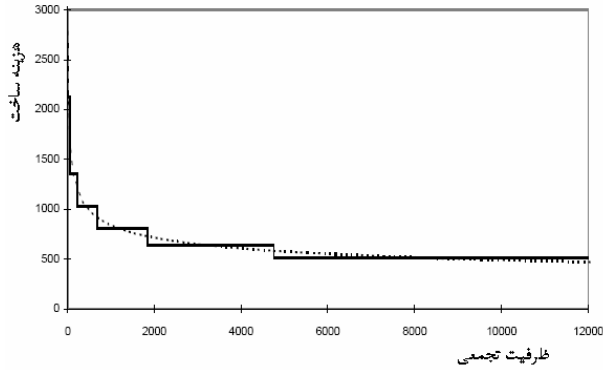
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$$\sum_{c,g} TRN_{yrcgs} \leq EXP_{yr}$$

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$$EXDR_{yrc} + \sum_{j=1}^y BLD_{jri} + \sum_{j=1}^y \sum_e BDI_{jrie} \leq CAPL_{cr}$$

r c

$$\sum_{i,d} ELI_{yri} \cdot EXDR_{yri} \cdot LHRS_i + \sum_{j=1}^y \sum_{i,d} ELI_{yri} \cdot BLD_{jri} \cdot LHRS_i + \sum_{j=1}^y \sum_{i,e,d} ELI_{yri} \cdot BDI_{jrie} \cdot LHRS_i - PINT \cdot GEL_{yrs} \leq 0$$

s y r

GEL

PINT

$\lambda$

$$C_{cy} = \sum_{i=1}^N \lambda_{c iy}$$

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$$\sum_{r,i,d} ISHR_i \cdot ELI_{yri} \cdot LHRS_i \cdot (EXDR_{yri} + \sum_{z=1}^y (BLD_{zri} + \sum_e TLOSS_{zre} \cdot BDI_{zrie})) + \sum_{r,n,d} RSHR_n \cdot ELR_{yri} \cdot LHRS_i \cdot OPR_{yrs} - RMIN_y \cdot \sum_r GEL_{yrs} \geq 0$$

C

s y

i

N

(ISHR)

$\lambda$

$\beta \alpha$

(RMIN)

$$TC_{cy} = \sum_{i=1}^N (\alpha_{ci} \cdot \delta_{c iy} + \beta_{ci} \cdot \lambda_{c iy})$$

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$\delta$

RMIN

$\beta$

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$$\beta_{ci} = \frac{TC_{c,i} - TC_{c,i-1}}{C_{c,i} - C_{c,i-1}}$$

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$$\sum_{r,c} CBLD_{yrc} \cdot BLD_{yrc} + \sum_{e,r,c} CBBDI_{yrec} \cdot BDI_{yrec} \leq BDGL_y$$

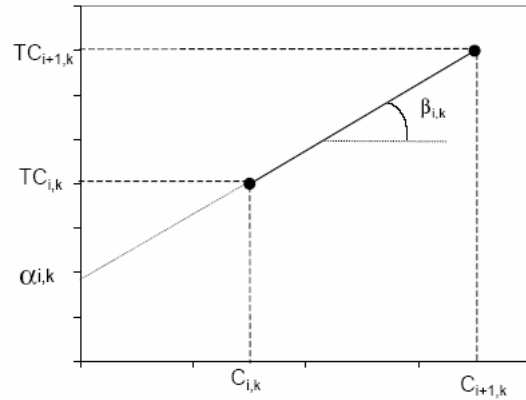


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$\alpha$  $( )$ 

$$\alpha_{ci} = TC_{c,i-1} - \beta_{ci} \cdot C_{c,i-1} \quad ( )$$

$$\begin{aligned} \lambda_{c iy} &\geq C_{c,i} \cdot \delta_{c iy} \\ \lambda_{c iy} &\leq C_{c,i+1} \cdot \delta_{c iy} \end{aligned} \quad ( )$$

 $\lambda$  $( )$  $( )$  $( )$ 

$$\sum_{i=1}^N \delta_{c iy} = \quad ( )$$

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$$\sum_{P=1}^i \delta_{c,P,y} \geq \sum_{P=1}^i \delta_{c,P,y+1} \quad ( )$$

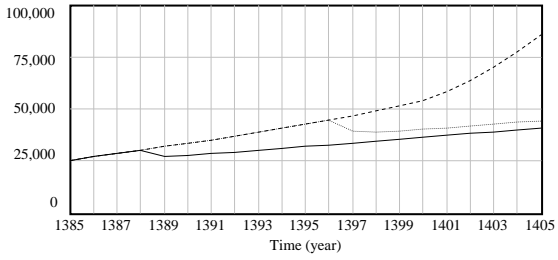
$$\sum_{P=i}^N \delta_{c,P,y} \leq \sum_{P=i}^N \delta_{c,P,y+1}$$

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$$IC_{cy} = TC_{c,y} - TC_{c,y-1} \quad ( )$$

IC

Demand



SDThs[h20,summer] : scenario1 —————  
 SDThs[h20,summer] : scenario2 .....  
 SDThs[h20,summer] : scenario3 - - - - -

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( EVPI)

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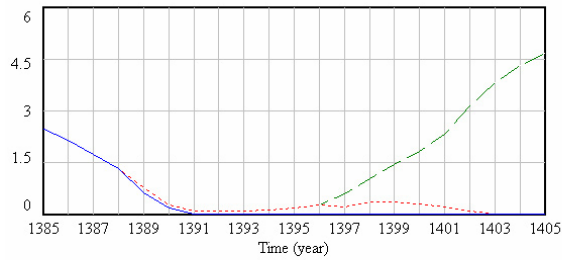
$$EVPI = HN - WS$$

WS

HN

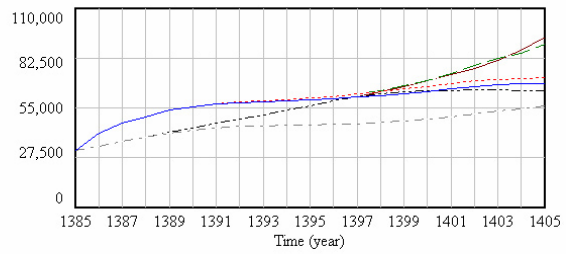
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ب) درصد تقاضای برآورده نشده تحت هر یک از سناریوهای تقاضا



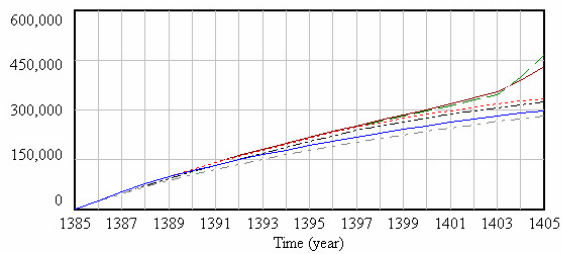
PUDe[generation and transition] : scenario1 — Dmnl  
PUDe[generation and transition] : scenario2 - - - - - Dmnl  
PUDe[generation and transition] : scenario3 - - - - - Dmnl

الف) روند تغییر ظرفیتهای موجود تحت هر یک از سناریوهای تقاضا



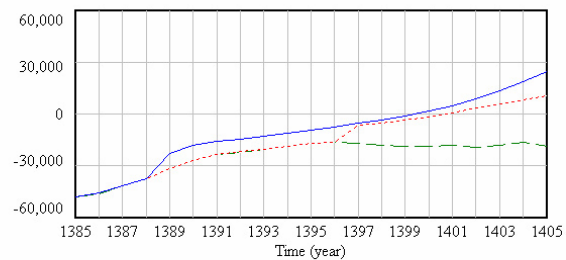
PCS[generation and transition] : scenario1 — MW  
PCS[generation and transition] : scenario2 - - - - - MW  
PCS[generation and transition] : scenario3 - - - - - MW  
PCS[generation and transition] : s1scenario1 - - - - - MW  
PCS[generation and transition] : s1scenario2 - - - - - MW  
PCS[generation and transition] : s1scenario3 - - - - - MW

د) مقایسه هزینه های صنعت برق تحت هر سناریو با طرح فعلی و طرح بپخته قطعی



TC : scenario1 — milliard rial  
TC : scenario2 - - - - - milliard rial  
TC : scenario3 - - - - - milliard rial  
TC : optscenario1 - - - - - milliard rial  
TC : optscenario2 - - - - - milliard rial  
TC : optscenario3 - - - - - milliard rial

ج) سود صنعت برق تحت هر سناریو



profitR : scenario1 —  
profitR : scenario2 - - - - -  
profitR : scenario3 - - - - -

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<sup>1</sup> Power System Expansion

<sup>2</sup> Extensive Form

MARKAL :MARKAL<sup>3</sup>

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<sup>4</sup> MESSAGE: Model for Energy Supply Strategy  
Alternatives and their General Environmental Impact

<sup>5</sup> International institute for Applied Systems Analysis

<sup>6</sup> WASP: Wien Automatic System Planning

<sup>7</sup> NEMS: National Energy Model System

<sup>8</sup> Expected Value of Perfect Information

<sup>9</sup> Here-and-Now

<sup>10</sup> Wait-and-See

<sup>11</sup> Robust Optimization

